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J. J. Pengra

LOCKHEED-CALIFORNIA COMPANY
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BURBANK, CALIFORNIA

CONTRACT NAS1-15599
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FOREWORD

This report was prepared by the Lockheed California Company, Lockheed Corporation, Burbank, California under the terms of Contract NAS1-15599. The test specimens were fabricated at the Lockheed Burbank, California facility and tested at Rye Canyon (Saugus), California Research Laboratory. The program was sponsored by the National Aeronautics and Space Administration, Langley Research Center, Hampton, Virginia and the United States Army Research and Technology Laboratory, Hampton, Virginia. Mr. W. T. Hodges was the technical representative of the contracting officer.

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STUDY OF THE INFLUENCE OF HOLE QUALITY ON COMPOSITE MATERIALS*

By J. J. Pengra

Lockheed-California Company

SUMMARY

The objectives of this report are to present the test data generated during the experimental investigation of holes of various quality levels in graphite/epoxy composites and, by evaluation of these test data, to develop meaningful accept/reject criteria for holes in graphite/epoxy composites. Fabricated from T300/5208 material the specimens tested were 3.05 mm (0.120 in.) and 4.32 mm (0.170 in.) thick, typical of airframe rib structure and thick cover areas. The thinner 3.05 mm specimens were laid up in a quasi-isotropic $(45, 0, -45, 90_2, -45, 0, 45)_3$ pattern and the thicker 4.32 mm specimens were laid up in a $(\pm45, 0_4, \pm45, 0_3, \pm45_2, 0_2)_S$ pattern. A 4.76 mm (3/16 in.) diameter hole was selected for this investigation because it is representative of a size commonly used in airframe construction.

An industry survey identified the three most prevalent hole flaws experienced during drilling of graphite/epoxy these were: (1) chipout of matrix material, (2) delamination of exit ply, and (3) oversize holes. Specimens with these hole flaws were fabricated for test comparison against high quality hole control specimens.

Tests performed consisted of pin loading the holes in static tension and static compression, as well as pin loading in completely reversed (R = -1) fatigue cycling. These tests were conducted in both dry laboratory air and hot moist air environments.

Results show that a hole chipout defect reduces the static and cyclic endurance characteristics. The oversize holes also lowered the cyclic pin bearing endurance, but this defect did not lower the static pin bearing characteristics. Delamination of the exit face ply during hole fabrication did not influence static pin bearing strength and the effect of this flaw on pin bearing endurance was not significant. However compression tests demonstrated a deleterious effect on compression strength for holes with chipout or delamination defects.

These results support a relaxation of graphite/epoxy composite delamination hole quality requirements for noncompression critical structure. However,

*The contract research effort which has led to the results in this report was financially supported by the Structures Laboratory, USARTL (AVRADCOM).

before this change can be permitted additional confirming tests are necessary. These tests would include shear, static compression pin bearing and cyclic pin bearing evaluations of various ply thicknesses and orientations. If this relaxation of hole delaminations requirements could be permitted, it could result in a cost savings for the use of graphite/epoxy composite structures as the delamination hole flaw is one of the two most frequent composite hole flaws.

INTRODUCTION

The use of current engineering materials including both metallic and composite materials in aircraft manufacturing dictate the use of drilled holes and mechanical joining for the foreseeable future. The airframe industry has a long manufacturing history of fabricating holes in metallic structure which has resulted in continuous fabrication improvements and refinements in quality requirements. The structural application of advanced composite materials to airframes, in place of metallic materials, must be done without compromising structural integrity. As there was little engineering test data and service experience on airframe parts fabricated from advanced structural composite materials, it was necessary to initially establish rather stringent hole quality requirements for this material. These stringent accept/reject requirements are relevant to commercial airframe with their extended long life/high reliability needs.

Stringent hole requirements for composite materials are also related to the nature of the flaws that are encountered during drilling through laminated structure. Flaws encountered, including chipout and delamination of plies, are quite different from those experienced during drilling of holes in metallic materials. Until the effect of composite hole flaws on structural integrity is determined, it is prudent to maintain cautious acceptance requirements.

A cautious approach to composite hole quality results in a cost and weight penalty. Increased application of composite materials to airframe depends on the efficient production of a durable, cost-affordable/lightweight structure. Production processes must be carried out in the most cost-effective manner consistent with quality levels that meet the durability requirements. The durability of composite material structures over the service life of an aircraft is dependent on the durability of the holes drilled in the structure.

The objective of this effort was to develop and validate acceptance criteria for drilled fastener holes in composite structure. This was initiated by an industry survey to determine the equipment and procedures currently in use for drilling holes in composite structure. In addition, the type, magnitude, frequency, and cause of defects in hole drilling were to be determined and the effects of these defects were sought.

In conjunction with the industry survey, a test method development effort was undertaken.

This report presents findings of the industry survey and the details of how the results were incorporated into the test program. The tests performed and their results are presented and discussed. Acceptance criteria for drilled holes in graphite/epoxy composite materials are proposed.

The units used for physical quantities in this report are given both in U. S. Customary Units and in the International System of Units (SI) (reference 1). The principal units used for measurement were the U. S. Customary.

Use of commercial products or names of manufacturers in this report does not constitute official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

INDUSTRY SURVEY

To aid in the development of a test program which would have maximum acceptance an industry questionnaire was circulated to determine methods being used to drill holes in graphite/epoxy composites, including imperfections encountered, their causes, and frequency. A total of 30 companies were surveyed and 17 responses were received. Results of this survey are presented in Appendix A. The findings can be briefly summarized as follows:

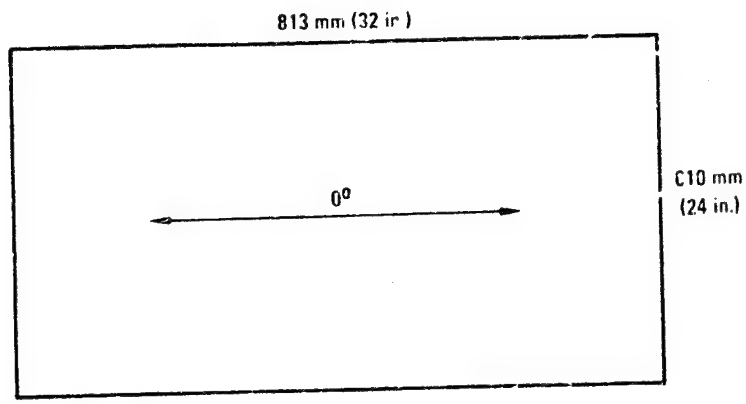
- Narmco T300/5208 graphite/epoxy was the most widely used system.
- Each, used carbide drills, but not necessarily exclusively.
- Drill presses, production tools, and hand drills are used rather equally.
- Most common hole tolerance is 0.076 mm (0.003 in.) total.
- Out of the 11 possible hole flaws suggested, respondents reported incurring a maximum of 9 of the 11 defects.
- A single respondent reported experiencing only one of the possible defects.
- Most frequently reported hole flaw: Chipout
  Second most frequent: Delamination
  Third most frequent: Oversize
  Fourth most frequent: Overheat
- Majority of the respondents have an accept/reject criteria for holes that is based on prior test data.

EXPERIMENTAL INVESTIGATION

Test Specimens

Materials - Narmco T300/5208 graphite/epoxy was used to fabricate all test specimens for this program. This system was shown to be common to many of the questionnaire respondents and is the system used in the Lockheed-California Company, NASA Advanced Composite Vertical Fin (ACVF) and Advanced Composite Aileron (ACA) programs, references 2 and 3 respectively. Approximately 15.9 kg (35 lb) of 305 mm (12 in.) wide, 0.13 mm (0.005 in.) prepreg tape, 41 percent resin content by weight material was acquired. The as-received material met the requirements of the applicable Lockheed Material Specification C-22-1379A/111.

Laminate Patterns. - Five panels with two thicknesses and ply orientations were laid up and cured. Panel details are as follows:



Number of Panels	Type	Ply orientation	Thickness mm	Thickness in.
1	Cover	$(\pm45/0_4/\pm45/0_3/\pm45_2/0_2)_S$	4.32	0.170
4	Rib	$(45/0/-45/90_2/-45/0/45)_S$	3.05	0.120

T300/5208 GRAPHITE/EPOXY

The five panels were laid up and cured to the general requirements of Lockheed Process Bulletin PB80-577. The cure cycle was:

1. Apply full vacuum.

2. Heat to 408 K (275^{o}F) ± 3 K (5^{o}F) @ 1-2 K (2-3^{o}F)/minute.

*3. Dwell at 408 K (275^{o}F) ± 3 K (5^{o}F) for 30 ± 1 minutes.

4. Apply .69 MPa (100 psi) ± .03 MPa (5 psi), when pressure of 0.14 MPa (20 psi) achieved vent vacuum to air.

5. Heat to 452 K (355^{o}F) ± 3 K (5^{o}F) @ 1-2 K (2-3^{o}F)/minute.

6. Cure 120 $\pm^{10}_{0}$ minutes @ 452 K (355^{o}F) ± 3 K (5^{o}F).

7. Cool to 333 K (140^{o}F) ± 3 K (5^{o}F) under pressure @ < 2 K (4^{o}F)/minute.

8. Cool to R.T.

*NOTE: dwell time starts when temperature reaches 402 K (265^{o}F).

The 4.32 mm (0.170 in.) thick panel represents the ACVF cover at the lower maximum thickness end. The four 3.05 mm (0.120 in.) panels were similar to an ACVF rib cap cross section and ply orientation.

Configurations. - Including spares, a total of 228 specimens were fabricated. Details of the pin loaded static and fatigue as well as the compression specimens are shown in figures 1 and 2. A 4.80 mm (3/16 in.) diameter test hole was used as it is a standard airframe fastener hole size. An edge distance to diameter ratio of 3 was selected for the pin bearing specimens. A group of compression specimens were fabricated without holes to permit determination of the basic compressive strength.

Fabrication procedures. A Lockheed-built saw with a silicon carbide 254 mm (10 in.) diameter by 3.18 mm (0.125 in.) wide blade operating at 3200 rpm with a 853 mm/min (2.8 ft/min) feed rate was used to cut the specimen blanks. Chip removal was provided by two methods: (1) Water soluable oil was sprayed on the wheel as a coolant, which also washed away graphite dust from the cut and (2) a dry vacuum system was employed.

Fiberglass tabs were bonded on with EA9309 Hysol adhesive for room temperature test specimens and FM400 adhesive for specimens to be environmentally conditioned followed by environmental testing.

The industry survey identified the three most prevalent flaws experienced when drilling holes in graphite composite. Listed in descending order of occurrence, they are:

- Chipout of matrix material from the hole wall.
- Exit side delamination.
- Oversize holes.

The test matrix for static and cyclic pin bearing specimens and compression specimens, is shown in table I. In addition to high quality hole baseline control coupons, specimens with the above three types of most frequent hole flaws were fabricated for evaluation.

The specimens were divided into four groups, namely Group I baseline control specimens tested dry, Group II environmental effect specimens, Group III thickness effect specimens tested dry, and Group IV compression specimens.

Special techniques were developed to produce consistent chipout and exit side delamination type flaws. Attempts were made to develop chipout type flaws by slant drilling the face of the hole wall with a small diameter bit. The use of a small Woodruff type cutter proved to produce a flaw more typical of chipout defects. The tool was ground from a No. 2 center drill shank and diamond coated on the cutting surfaces, the details of which are shown on figure 3.

To make the chipout defect the special cutter was run at 62 000 rpm (2100 sfpm) in an air driven Vulcanaire unit. The tool was run dry and manually fed into the hole to the desired depth of 0.381 mm (0.015 in.). Dust was removed by vacuum.

To generate a consistent delamination type flaw, a standard configuration carbide twist drill (Lockheed tool EL302N19-4) 4.84 mm (0.1905 in.) in diameter was used. Various speed and feed combinations were tried until the desired amount of repeatable delamination was obtained.

Oversized holes were made with the same drill configuration. For these specimens, the drill diameter was increased in size to give the oversize condition, the balance of the drilling parameters remained the same as used to make baseline high quality holes.

The 4.84 mm (0.1905 in.) diameter holes for the baseline control and chipout type flawed specimens were made with EL302N19-4 carbide twist drills. A SIP Jigbore was used for drilling. Cutting speed was 2100 rpm (105 sfpm) with a 0.020 mm/rev (0.0008 ipr) feed rate. Exit side backup was provided by drilling into masonite. Drilling was conducted dry with the chips and dust removed by vacuum.

As discussed, the special diamond coated tool was used to generate the chipout type flaw. Depending on the specimen thickness and the type of loading, the chipouts were positioned as shown in figure 4. In the 3.05 mm (0.120 in.) thick specimens the chipouts were offset (0.13 mm) (0.005 in.) from the centerline to clear the two 90-degree plies which were symmetrical to the centerline. For the 4.32 mm (0.170 in.) thick specimens, the chipouts were on the centerline which had two principal load carrying 0-degree direction plies on either side of the centerline. For both the static and fatigue specimens, the two chipouts were on the centerline of the loading direction as it was felt that the mode of failure would be by pin bearing face compression. The chipouts in the compression specimens were also offset to the ply layup center, but were at right angles to the compression loading direction. The probable mode of failure for these compression specimens dictated a 90-degree position as critical as they would fail by delamination across the reduced area.

Two special chipout type flawed specimens were fabricated. These consisted of adding a second chipout flaw on both tension and compression pin bearing surfaces of thicker 4.32 mm (0.170 in.) Group III specimens. This added flaw was placed 0.33 mm (0.013 in.) above the first flaw and was advanced 0.38 mm (0.015 in.) into the hole. The flaw in specimen III S7-5 had the standard 0.33 mm (0.013 in.) thickness and the added flaw in specimen III S7-4 was thicker at 0.58 mm (0.023 in.).

As shown in table II, the delamination of the exit 45-degree ply 1.78 mm (0.070 in.) wide by 5.1 to 6.4 mm (0.20 to 0.25 in.) long were produced using the same carbide drill but operating at a reduced speed of 980 rpm and a high feed rate 0.0635 mm/rev (0.0025 ipr). In addition no backup was used.

The oversized holes were desired to be 5.00 to 5.03 mm (0.197 to 0.198 in.) in diameter which just exceeds the maximum oversize condition that is permitted without requiring a special oversize fastener. To develop this condition, a larger drill at 5.03 mm (0.198 in.) diameter was used at the same surface speed and feed rate as was used to drill the high quality baseline specimens, see table II. The four 6.35 mm (0.25 in.) diameter holes in the static and fatigue specimens for attaching to the lower clevis were drilled to size in a drill fixture. Holes were coordinated to align with the clevis and position the test hole on the test fixture centerline. No attachment holes were made in the compression specimens. These specimens were held in hydraulic grips during the compression loading cycle.

Test Procedures

Initial inspections. - All test holes were dimensionally, visually, and 1, 4 diiodo-butane (DIB) enhance radiographically inspected prior to test. The following procedure was used for DIB inspection.

1. Clean the hole with a dry air blast.

2. Apply shot peening masking tape to the entrance side of the specimen hole, covering the specimen hole.

3. Apply DIB solution as follows:

   a. Incline specimen width approximately 45 degrees to the horizontal. Note: This is done to preclude entrapment of air in chipout defects.

   b. Using a dropper, apply solution slowly, filling the hole.

   c. Allow solution to stand 10 to 15 minutes, removing it with the dropper.

4. Remove tape.

5. Wipe dry with a clean dry cloth.

6. Within 1 hour of solution removal, step 3.c, perform radiographic inspection in accordance with Lockheed LCP72-2015 (MIL-STD-453). Radiographs shall have a film density of 1.70 ±0.30.

Environments. - The environmental conditioning of the Group II specimens from this program was conducted by the method developed for the NASA Advanced Composite Vertical Fin contract, reference 2. This conditioning attempts to simulate the 1.0 to 1.3 percent moisture picked up by weight when exposed to 67 to 70 percent relative humidity for extended periods. Specimens so conditioned were immersed in 338.8 K (150°F) water for 26 days. Each group of specimens was accompanied by three calibration coupons made from the same laminate panel.

The Group II environmental specimens were held in their sealed bags at room temperature and tested within 10 days of completion of the moisture conditioning. This environmental test was performed in a moist air chamber at 355.4 K (180°F). Moisture was provided to the test chamber by bubbling air at 3.45 KPa (0.5 psi) through 344.3 K (160°F) deionized water. The air was circulated through the test chamber, providing 80 to 90 percent relative humidity, by a hot air gun controlled by a rheostat provided the 355.4 K (180°F) temperature. This temperature was recorded by a thermocouple connected to a continuous recorder.

Static and cyclic pin bearing tests. - After some preliminary development efforts, the method selected for determining the effect of hole quality in graphite/epoxy structure consisted of pin loading the holes in static tension and compression as well as pin loading the holes in completely reversed fatigue cycling. This effort concentrated on compression loading; tension

dominated spectrum fatigue and cyclic fatigue loading did not induce additional degradation of laminates with holes and slots (reference 4). Compression dominated fatigue loading did degrade strength of laminates containing holes and slots as shown in references 4 and 5. The system developed from trial tests consisted of a double clevis arrangement. The lower part of the specimen was bolted to a clevis and then the upper part of the specimen, which contained the test hole, was placed between the upper clevis plates. The load pin was then inserted through holes in the loading plates and the test hole. The threaded loading pin was then tightened finger tight, causing the loading clevis plates to bear against the specimen face, restricting hole face deformation during testing. This restriction of the specimen surface was done to simulate lapjoined structure. Shimming provided this specimen face restriction for the thicker Group III specimens, as well as the thinner Group I and II specimens.

A linear voltage differential transformer (LVDT) system was attached to the specimen in such a manner as to measure the movement of the loading pin in relation to the specimen. Pin displacement, was an effective method for monitoring degradation of the specimen hole during testing.

Figure 5 shows the static and fatigue pin bearing setup, figure 6 shows an X-Y plotter, and figures 7 through 10 show the details of the fixtures used for these tests.

Static and cyclic pin bearing tests were performed in a electrical controlled 227 000 kg (500 000 lb) fatigue machine. The loading heads were aligned to ±0.05 mm (±0.002 in.) which was maintained by fixtures installed on both heads.

An X-Y plotter, as shown in figure 6, was used to record the loading pin deflections during testing. By this means specimen load as a function of pin displacement was plotted for each static specimen. This type of a curve was also plotted for each cyclic pin loaded specimen prior to and after being fatigue tested.

A 4.81 mm (0.1895 in.) diameter pin was used for static testing. For the fatigue tests pins of slightly varying diameters were provided to minimize misfit between specimen hole and loading pin. A new pin was used for each fatigue test. Other than the oversize hole specimens, a push fit of the pin was used. This fit consisted of pushing the pin through the contacting loading hole without having to use more than finger force. The clearance between the loading pin and the fatigue specimen hole was less than 0.02 mm (0.001 in.). The initial pin deflection under load, which is a function of pin mismatch, was less than 0.20 mm (0.008 in.) for all fatigue specimens tested other than those with oversize holes.

A fatigue cycle stress ratio (R) of -1.0 was used as this would subject both tension and compression faces of the hole to equivalent pin bearing compression loading thereby increasing the sensitivity of the test. Loads of 340, 397, and 454 kg (750, 875, and 1000 lb) were selected for fatigue testing

the Groups I and II 3.05 mm (0.120 in.) thick specimens. Preliminary cyclic tests showed that loads in the range of 40 to 65 percent of static pin bearing strength were effective in detecting hole quality influences.

A slow fatigue cyclic rate of 1 Hz was used to permit accurate periodic recording of loading pin deflection during fatigue testing. Fatigue testing of each specimen continued until the initial pin deflection had increased 40 percent, or 200 000 load cycles had been applied.

During fatigue testing the hard chromium plated and honed layer on the upper clevis plate loading holes flaked, see figure 8. To improve load bearing capabilities of the test fixture, C-2 carbide bushings 10.16 mm (0.400 in.) in diameter were used in the clevis plate loading hole with approximately 0.013 mm (0.0005 in.) of interference. These bushings measured 4.82 - 4.84 mm (0.1900 - 0.1905 in.) diameter after installation.

Compression tests. - In addition to the pin loading tests, standard compression tests were performed to evaluate the effect of hole quality on this characteristic. These compression tests consisted of testing the specimens in a full platten supported 45 400 kg (100 000 lb) closed loop test machine with servo hydraulic system. A cross head loading rate of 1.27 mm/min (0.05 in/min) was used. This system was used for the extensive compression tests of epoxy composites reported in reference 6.

A 50.8 mm (2.00 in.) extensometer was attached to the compression specimens without holes to record strain during loading. Load versus pin deflection curves were plotted for each specimen. Cross head movement was recorded as strain for specimens with holes.

Periodic and final inspection. - After completion of testing all pin bearing specimens were DIB radiographic enhanced inspected as outlined previously. In addition selected fatigue specimens were DIB inspected periodically during testing to monitor damage detection and growth. The cyclic pin bearing specimens were visually inspected to determine which of the bearing faces had experienced damage.

TEST RESULTS AND DISCUSSION

Pretest Inspections

The as-received prepreg material met the applicable batch acceptance test requirements. The five C-scans from the ultrasonic inspection showed the cured panels to be void free and the product control test results as presented in table III, showed acceptable mechanical characteristics and resin content.

Midway through the specimen fabrication the saw machine coolant system was replaced with a dry vacuum system. As a consequence, some of the sawn edges, cut dry, exhibited slight matrix material missing on the specimen edge. Because the critical test area was around the hole this slight difference in edge quality, although visible, was believed to have no affect on test results.

All specimens tested met the dimensional requirements of figures 1 and 2. Visual examination revealed the specimens to be of the quality desired.

Specimens that were to have delaminations were delaminated on the exit face one ply deep, approximately 6.4 mm (0.25 in.) in length and 1.78 mm (0.070 in.) wide. Figures 11 and 12 are photographs of typical delamination specimens, shows the nature and consistency of the delamination developed. DIB enhanced radiographs, figure 13, of the delaminated specimens show that this flaw was consistent and only the one 45 degree face ply deep.

The oversize hole specimens measured 5.004 to 5.029 mm (0.1970 to 0.1980 in.) in diameter. Visual and DIB enhanced radiographic inspection showed the specimens to be free of defects.

The chipout type flaws generated on both the pin bearing tension and compression faces of the hole were located in the area desired. Figure 14 shows a typical 4.32 mm (0.170 in.) thick, Group III specimen section with the chipout type flaw located in the center of the specimen. The chipout flaw in the thinner 3.05 mm (0.120 in.) thick, Group I and II specimens was moved off center to assure that the principal load carrying 0 degree plys of this $(45, 0, -45, 90_2, -45, 0, 45)_3$ layup were removed. This flaw is shown in figure 15 photograph of a sectioned specimen. The consistent geometry of the chipout type flawed specimens is demonstrated by the typical DIB enhanced radiograph photopositive of figure 16.

The baseline high quality specimens did not exhibit any flaws from DIB radiographic inspection and their visual appearance was excellent. One can see the condition of these holes in the figures 14 and 15 photographs which represent the high quality hole with chipout flaws superimposed.

Environmental Conditioning

A calibration 25.4 x 50.8 mm (1 x 2 in.) coupon was evaluated prior to moisture exposure of the Group II environmental test specimens. This coupon was weighed and then dried for 7 days at 366.4 K (200°F). The difference between the before and after drying weight was called residual moisture and is recorded in percent. Two additional coupons accompany the pin bearing Group II environmental specimens during the moisture pick-up environmental conditioning. After conclusion of this 26-day water immersion cycle, the coupons are weighed and the increase in weight or moisture pick-up is noted.

Four groups of specimens were exposed to the immersion cycle and the moisture pick-up varied from 0.98 to 1.01 percent. This represents approximately two-thirds saturation which is typical for high moisture tests on T300/5208 graphite material, reference 2.

Static Pin Bearing

Results of static tension and compression pin bearing tests are presented in tables IV and V respectively. Both tension and compression loading modes were used to detect any differences in the load deflection behavior of the composite material.

Figure 17 shows a typical load-deflection plot obtained during tension mode testing and figure 18 shows a similar plot from a compression mode test. A full cycle load deflection trace is presented in figure 19 wherein a tension load was applied, removed and a compression load applied and removed. These curves highlight the difference in load deflection as a function of load direction for graphite epoxy material.

Another aspect of the load deflection curves is their linearity up to damage initiation and then failure (damage propagation) evidenced by the abrupt change in slope. Because of this material behavior, the load and deflection to damage initiation is reported rather than yield load that is typical of polycrystalline materials. Ultimate load is reported, however, it is felt that these data are of slight significance.

There are several significant points to be seen from the completed static pin bearing tests:

1. There is little yielding of the material prior to failure.

2. There is a definite point of damage initiation, with linear load-deflection up to the point of damage initiation.

3. There is a significant difference in the slope of the load-deflection curve for tension versus compression loading modes. This is due to the differences in response to tension and compression pin loading.

4. Compression loading appears to result in a lower load to damage initiation than tension loading. This is attributed to delamination of plys that occurs more readily during compression loading.

5. Total deflection to damage initiation is basically the same for both loading directions, both laminate thicknesses, and both environmental exposure conditions.

The static tension mode pin bearing data is summarized in figure 20, showing the large effect of the chipout type flaw and hot moist air environment. The average pin bearing strength of the 3.05 mm (0.120 in.) thick chipout type flawed specimens was 14 percent below that of the high quality baseline specimens average strength. This reduction exceeds the 7 percent reduction in bearing area due to chipout. The delamination and oversize holes did not have an effect on the static pin bearing strength when tested in a tension mode. The hot moist air environment did have an effect on the baseline static pin bearing strength reducing this characteristic 6.5 percent based on the average strength.

Chipout type defects appear to lose some of their deleterious effect with increasing specimen thickness, refer to figure 20. There was only a 3 percent reduction in the average pin bearing strength for the chipout specimens made from the thicker laminate when compared to similar thickness high quality baseline specimens. This size effect phenomenon is also noted in the cyclic pin bearing results.

The chipout type defect was also found to reduce the bearing strength when the static tests are performed under a compression mode. As summarized in table V, there is some indication that delamination type defects lower the compression bearing strength.

All of the static pin bearing loaded test specimens were inspected after testing by both visual and DIB enhanced radiographic methods. Those specimens that were loaded to just below ultimate load did not exhibit any incipient damage. Specimens loaded to ultimate load did exhibit damage to the matrix by DIB inspection. These specimens failed by a bearing mode, see reference 7, which if allowed to continue became a shearout failure.

Cyclic Pin Bearing

The cyclic pin bearing tests were continued until a pin deflection of 140 percent of the initial pin deflection was achieved or until 200 000 cycles were completed. The cut-off point of 40 percent increase in pin deflection was selected after some test specimens were cycled well beyond the 140 percent of initial deflection value. Care was taken to evaluate specimens in this manner with both relatively low initial pin deflections of 0.10 mm (0.004 in.) and high pin deflections up to the maximum of 0.20 mm (0.008 in.). The pin deflection versus load cycles for these specimens are plotted in figure 21. Although these data are plotted on a log scale it clearly shows that once the specimen flaw began to propagate the rate of deterioration was rather rapid. Increase of pin deflection under cyclic loading to 140 percent of initial pin deflection appears to be a meaningful cut off point.

Pin deflection versus cycle curves for the four hole conditions tested in dry air are presented in figures 22, 23, 24, and 25 respectively. There are some slight differences in the nature of these curves. At the ±397 kg (±875 lb) load the chipout specimens of figure 23 deteriorated much sooner than the other specimen types. This is attributed to the chipout flaw

generating critical midply delamination under high pin bearing. The increase in the percentage of pin deflection change for the specimens containing oversize holes appears to be lower than the other specimen hole types. This is attributed to the high initial pin deflection of these specimens due to the loading pin misfit. It should be noted that in spite of the large initial pin deflection of the oversize specimens once they started to deteriorate they steadily continued and failed before the 200 000 cycle limit.

Apparent small reductions in pin deflections during cyclic testing is attributed to accuracy of measuring methods.

Attempts to nondestructively detect the onset of damage during cyclic testing were successful. The DIB inspection method used detected damage to specimens when they had experienced increased pin deflection to as little as 112 percent of initial pin deflection. Examples are shown in figures 26 and 27 of DIB enhanced radiographs of delamination and chipout type flawed specimens taken before, during and after cyclic testing. Pin deflection versus load cycle plots of the two specimens, I57 and I69, used for these DIB radiographs are shown in figure 21.

Figure 28 shows the surface characteristics of a typical failed specimen containing a chipout defect. Even though chipout specimens tended to have the original defect obliterated, flaw growth was clearly evident by DIB examination.

The cyclic pin bearing data generated in this program for the thin, 3.05 mm (0.120 in.) and 4.32 mm (0.170 in.) thick laminate specimens are presented in tables VI and VII respectively. These data are summarized in in the figure 29 bar chart showing each specimen life. The deleterious effect of chipout and oversize defects is readily evident while the influence of delaminations appears rather small. At the ±397 kg (±875 lb) load level, which is approximately 50 percent of the load that produces an abrupt change in slope on the load deflection curve (initial damage load), the delamination defect showed no effect on the endurance characteristics. At the high alternating load of ±454 kg (±1000 lb) the delamination type defect appeared to be of small effect on endurance.

The moist environment had the most significant effect on the endurance characteristics, reducing the minimum baseline endurance for the 3.05 mm (0.120 in.) specimens tested at ±397 kg (±875 lb) from 80 000 cycles to 6000 cycles.

The chipout defect had a smaller influence on the cyclic endurance characteristics in the 4.32 mm (0.170 in.) thick specimens than on the thinner 3.05 mm (0.120 in.) thick specimens.

Compression

The compression data are presented in table VIII and graphically summarized in figure 30. These results indicate an average of 9 percent reduction in compression strength due to delamination flaw and an average of 4 percent reduction in compression strength due to chipout. This is attributed to the chipout and delamination flaws acting as initiation sites for delamination mode failures when loaded in a compression columnar type manner.

Probability Data Analysis

The test data generated were plotted on normal probability paper. This was done within each set of n replicated tests by arranging the results in ascending order and plotting them as the midpoints of n equal increments on a probability scale. For example, the results of five compression strength tests of specimens with chipout damage are plotted in figure 31 starting with the lowest strength at probability values of 10, 30, 50, 70 and 90 percent, which are the midpoints of five equal increments.

The straight line fitted through the data on these graphs is a normal probability distribution. The mean of this distribution is the intercept at 50 percent probability, and the standard deviation is proportioned to the slope of the line. One standard deviation from the mean occurs at probability values of 16 percent and 84 percent. In general, the test results in this program have too few replications to substantiate that the distribution is indeed normal. Nevertheless, the best fit straight line through each set of data is calculated and shown as a visual aid in making the data comparisons.

The abscissa of these graphs is the estimated probability that the next specimen tested will have a lower strength (or for the fatigue data, shorter life) than the plotted strength (or life). In figure 31 for example, the estimated probability is 16 percent that the compression strength of an arbitrary specimen with chipout damage will be lower than 352 MPa (51.1 ksi).

The compression strength data are plotted in figure 31. Specimens with chipout damage had 3 percent lower strengths than baseline undamaged specimens, which from a practical standpoint seems negligible. However, large scatter was experienced in the compression strengths of specimens with delamination defects. As a result, the 5 percent probability value for the strength with delamination is 302 MPa (43.7 ksi), compared to 359 MPa (52.0 ksi) for the baseline, a 16 percent strength loss. From a reliability standpoint, the 5 percent probability value is even more important than the mean. However, it is an extremely questionable procedure to estimate the 5 percent probability value using only 4 data points.

Figure 32 shows the tensile strength data for the thinner 3.05 mm (0.120 in.) laminate. For this thickness there appears to be about 14 percent loss of tensile strength due to chipout. The data for delaminations show lower scatter and a slightly higher strength than the baseline.

Whereas the oversized hole tended to increase the strength compared to the baseline, it also increased the scatter. This high scatter causes concern, because the oversized hole appears, by extrapolation, to be very detrimental at the 1 percent to 5 percent probability levels.

Figure 33 shows tension strengths for the thicker 4.32 mm (0.170 in.) layup. For this thickness the mean strength is not significantly affected by chipout, but the larger scatter leads to an estimated strength reduction of 16 percent at the 5 percent probability level. Caution is again encouraged in accepting this estimate at face value, since it is based on only 5 data points.

Probability plots of the fatigue life data are given in figures 34 through 36. Log (life) is plotted, so a straight line is a normal distribution on log (life), also called a lognormal probability distribution. Tests were terminated if failure did not occur within about 200 000 cycles, and there were a number of these runouts. Where there are runouts, the best-fit line is difficult to calculate. For the data sets with one-or-more runouts, a straight line is visually faired through the failure points on the left side of the graph, with a steep-enough slope to place the line near or above the runout points.

Figure 34 shows the fatigue data for tests conducted in dry air at an applied maximum load of 454 kg (1000 lb). All three forms of damage appear to reduce the test life in comparison to the baseline. The reductions due to chipout or oversize hole appear to be significant, amounting to a factor of 5 to 8 on life. Delamination caused a significant reduction in the estimated mean, but due to lower scatter in the delamination data, the 1 percent probability estimates for baseline and delamination are nearly equal. Note that these low-probability-level estimates are based on large extrapolations of sparse data: More data would be needed before confidently concluding that delaminations significantly degrade fatigue reliability.

Figure 35 shows the data in laboratory air at a maximum load of 397 kg (875 lb). The chipout specimens were tested with only two runouts. The chipout condition caused about a factor of 4 reduction in fatigue life compared to the baseline. Delamination exhibits improved life while there is a small detrimental effect of the oversized hole. Neither of these latter effects can be considered significant, because each of the sample sizes included only two specimens that actually failed, the remaining samples being runouts.

Figure 36 compares the environmental fatigue lives with and without chipout damage. Based on limited data which include only three baseline specimens, the chipout condition has more scatter and a shorter estimated life, especially at and below the 20 percent probability level.

The observations from figures 31 through 36 may be summarized as follows. Except in the case of compression strength, chipout consistently degrades the structural performance. Similarly, limited data on oversized holes show a degradation in both fatigue life and static tensile strength. The data for

delaminations, however, are mixed. There are indications that delamination may not degrade fatigue life or tensile strength significantly, but the compression strength appears to be lower and more subject to scatter.

CONCLUSIONS

1. The three most frequent flaws encountered during fabrication of holes in graphite/epoxy composite material are; (1) chipout, (2) delamination of exit ply, and (3) oversize holes.

2. Relaxation of acceptance requirements for chipout defects and oversize condition in holes in graphite/epoxy composite material does not appear possible due to the exhibited influence of these flaws on structural characteristics.

3. Relaxation of delamination requirements for holes fabricated in graphite/epoxy composites may be possible with additional supporting data.

4. High temperature moist environment has a significant effect on the cyclic structural characteristics of graphite/epoxy structure with holes. Minimum static strength of the high quality control specimens tested was reduced 10 percent due to this environmental testing. The minimum pin bearing cyclic life of the high quality, control specimens tested was reduced from 80 000 cycles to 6000 cycles.

5. Nondestructive test method using 1, 4 diiodo-butane and radiographic inspection has capability to detect significant pin bearing cyclic loading damage to holes in graphite/epoxy material.

RECOMMENDATIONS

Further testing of single ply delamination flaws is recommended to solidify the observed trends. These tests would include alternate pin loaded cyclic tests in addition to static pin bearing compression tests. There appears to be a reasonable likelihood that, after more conclusive testing, delamination requirements could be relaxed.

PROPOSED ACCEPT-REJECT CRITERIA

Based on the limited test data generated on this program, the proposed accept/reject criteria for drilled hole quality in graphite/epoxy is presented in table IX. No changes are proposed for acceptance criteria of chipout or oversize conditions because of their deleterious effect on structural integrity. Delamination hole defects lower compression strength characteristics

but this defect appears not to influence pin loaded static or cyclic characteristics. Static compression pin loading and additional reverse pin loading cyclic tests are necessary before the delamination requirements can be relaxed.

TABLE I. TEST MATRIX - NUMBER OF SPECIMENS TESTED

Hole Type Load	Static Pin Bearing[1]				Constant Amplitude Pin Bearing Fatigue Tests, R = -1.0, f = 1 Hz									Compression			
	Baseline[2] High Quality	Chip Out Defect	Delamination Defect	Oversize Defect	Baseline High Quality[2]			Chipout Defect		Delamination Defect		Oversize Defect		No Hole	Baseline High Quality Hole	Chipout Defect	Delamination Defect
					340.5 kg	397 kg or 568 kg[4]	454 kg	397 kg or 568 kg[4]	454 kg	397 kg	454 kg	397 kg	454 kg				
Group I Basic Program Dry t = 3.05mm (0.120 in.)	11	10	8	8	3	6	3	11	6	7	6	4	3	–	–	–	–
Group II Environmental Effect[3] t = 3.05mm (0.120 in.)	11	9	–	–	–	3	–	7	–	–	–	–	–	–	–	–	–
Group III Thickness Effect Dry, t = 4.32mm (0.170 in.)	8	5	–	–	–	4	–	8	–	–	–	–	–	–	–	–	–
Group IV Compression	–	–	–	–	–	–	–	–	–	–	–	–	–	10	10	6	5

Notes
(1) ASTM E-238 some specimens loaded to a strain below failure and DIB and destructive evaluated..
(2) Baseline specimen holes fabricated by jigbore with carbide tool with no visual or DIB radiograph defects.
(3) Precondition 26 days in water at 338.8 K (150°F) prior to testing at 355.4 K (180°F) in moist air.
(4) Group I and II 3.05mm (0.120 in.) thick specimens fatigue tested at a load of 397 kg (875 lb). Group III 4.32mm (0.170 in.) thick specimens fatigue tested at a load of 568 kg (1250 lb).

TABLE II. HOLE FABRICATION METHODS

Type of Hole	Drill Type	Drill Diameter	Drill Speed rev/min. (surface ft./min.)	Drill Feed	Final Diameter
Control	Carbide	4.84 mm (0.1905 in.)	2100 (105)	0.0203 mm/rev. (0.0008 in./rev.)	4.83 - 4.84 mm (0.1900 - 0.1905 in.)
Chipout(1)	↓	↓	↓	↓	↓
Delamination	↓	↓	980 (50)	0.0635 mm/rev.(2) (0.0025 in./rev.)	↓
Oversize	↓	5.03 mm (0.1980 in.)	2000 (105)	0.0203 mm/rev. (0.0008 in./rev.)	5.00 - 5.03 mm (0.197 - 0.198 in.)

(1) Chipout generated by advancing a 0.33 mm (0.013 in.) x 3.33 mm (0.131 in.) diameter Woodruff keyway cutter into the hole face 3.81 mm (0.15 in.).

(2) 6.35 mm (0.25 in.) long, 1.78 mm (0.070 in.) wide delaminations generated by using no back up on the exit side.

TABLE III. QUALITY CONTROL DATA FOR TEST PANELS

Panel ID	Thickness mm (inch)	Resin Content %	Specific Gravity	Short Beam Shear MPa (ksi) 355.4 K (180°F) Wet	Compressive Strength MPa (ksi) 355.4 K (180°F) Wet
IVM1362	4.32 (1) (0.170)	27	1.57	52.2 (3) (8.0)	706.7 (102.5)
Requirements		26 to 30	1.56 to 1.60	62.1 (9.0)	676.2 (98)
IVM1363	3.05 (2) (0.120)	27	1.57	53.8 (7.8)	540.6 (78.4)
2VM1363		27	1.56	55.2 (8.0)	563.3 (81.7)
1VM1364		27	1.57	53.1 (7.7)	573 (83.1)
2VM1364		26	1.57	52.4 7.6	537.8 (78.0)
Requirements		26 to 30%	1.56 to 1.60	48.3 min (7.0) min	483 min (70) min

(1) 4.32 mm (0.170 in.) material layup $(\pm 45, 0_4, \pm 45, 0_3, \pm 45_2, 0_2)_S$

(2) 3.05 mm (0.120 in.) material layup $(45, 0, -45, 90_2, -45, 0, 45)_3$

(3) Short beam shear specimens taken from thin edge of panel, acceptable results by MRB action.

TABLE IV. STATIC PIN BEARING TEST RESULTS - TENSION MODE

Specimen Group and Type	Specimen No.	Initial Damage Load		Ultimate Load		Bearing Stress at Damage Load		Deflection						Slope (Bearing Stress/Deflection)	
								Initial		Damage		Total			
		kg	Pound	kg	Pound	MPa	psi	mm	in.	mm	in.	mm	in.	MPa/mm x 10^{-3}	psi/in. x 10^{-6}
Group I t=3.05 mm (0.120 in.) Dry															
Baseline	1-1	749.1	1650	Not Noted		501.6	72 750	0.0609	0.0024	0.1270	0.0050	0.1880	0.0074	3.95	14.55
	1-2	794.5	1750	Not Noted		527.5	76 500	0.0584	0.0023	0.1016	0.0040	0.1600	0.0063	5.20	19.13
	1-3	862.6	1900	Not Noted		568.1	82 400	0.0787	0.0031	0.1092	0.0043	0.1880	0.0074	5.20	19.16
	1-4	839.9	1850	1044	2300	557.8	80 900	0.0559	0.0022	0.1041	0.0041	0.1600	0.0063	5.36	19.73
	1-5	(803.6)	(1770)	Not Noted		(528.9)	(76 760)	0.0559	0.0022	(0.1219)	(0.0048)	(0.1778)	(0.0070)	(4.34)	(15.99)
	1-6	(567.5)	(1250)	Not Noted		(384.5)	(55 810)	0.0711	0.0028	(0.1321)	(0.0052)	(0.2032)	(0.0080)	(2.91)	(10.73)
	1-7	(794.5)	(1750)	Not Noted		(529.4)	(76 840)	0.0381	0.0015	(0.1270)	(0.0050)	(0.1651)	(0.0065)	(4.18)	(15.37)
	1-8	(794.5)	(1750)			(528.1)	(76 650)	0.0762	0.0030	(0.1270)	(0.0050)	(0.2032)	(0.0080)	(4.16)	(15.33)
	1-9	758.2	1670	1135	2500	515.9	74 880	0.0635	0.0025	0.1397	0.0055	0.2032	0.0080	3.70	13.61
	Average	800.0	1760		Average	533.9	77 486						Average	4.68	17.24
Chipout	1-11	681.0	1500	730.9	1610	450.8	65 430	0.0609	0.0024	0.1041	0.0041	0.1651	0.0065	4.33	15.96
	1-12	703.7	1550	785.4	1730	478.1	69 390	0.0813	0.0032	0.0940	0.0037	0.1753	0.0069	5.09	18.75
	1-13	703.7	1550	771.8	1700	468.2	67 950	0.0813	0.0032	0.1143	0.0045	0.1956	0.0077	4.10	15.10
	1-14	658.3	1450	783.2	1725	439.8	63 830	0.0940	0.0037	0.0838	0.0033	0.1778	0.0070	5.25	19.34
	1-15	670.0	1475	817.2	1800	443.7	64 400	0.1016	0.0040	0.0889	0.0035	0.1905	0.0075	5.00	18.40
	IS13-1	703.7	1550	749.1	1650	466.2	67 670	0.0889	0.0035	0.1016	0.0040	0.1905	0.0075	4.60	16.92
	1-20	703.7	1550	703.7	1550	464.4	67 400	0.0127	0.0005	0.1016	0.0040	0.1143	0.0045	4.58	16.86
	Average	690.0	1520		Average	458.7	66 580						Average	4.71	17.33

NOTE: Specimens with data in parenthesis ( ) were not tested to damage, therefore, these data were not used to determine the averages recorded.

TABLE IV. STATIC PIN BEARING TEST RESULTS - TENSION MODE (CONTINUED)

Specimen Group and Type	Specimen No.	Initial Damage Load		Ultimate Load		Bearing Stress at Damage Load		Deflection						Slope (Bearing Stress/Deflection)	
								Initial		Damage		Total			
		kg	Pound	kg	Pound	MPa	psi	mm	in.	mm	in.	mm	in.	MPa/mm x 10^{-3}	psi/in. x 10^{-6}
Group I															
Delamination	I-21	805.8	1775	828.6	1825	561.8	81 540	0.0503	0.0020	0.1448	0.0057	0.1956	0.0077	3.88	14.30
	I-22	805.8	1775	874.0	1925	540.6	78 470	0.0203	0.0008	0.1651	0.0065	0.1854	0.0073	3.28	12.07
	I-23	851.2	1875	874.0	1925	555.9	80 680					0.2030	0.0080		
	I-24	839.9	1850	862.6	1900	561.1	81 410					0.1778	0.0070		
	I-25	839.9	1850	851.2	1875	563.5	81 780					0.1778	0.0070		
	I-S12-5	(635.6)	(1400)	Not Determined		(417.0)	(60 520)	0.0965	0.0038	(0.0813)	(0.0032)	(0.1778)	(0.0070)		
	Average	828.5	1825		Average	556.5	80 780						Average	3.58	13.17
Oversize	I-26	612.9	1350	931	2050	429.9	62 400	0.1372	0.0054	0.1067	0.0042	0.2438	0.0096	4.03	14.85
	I-27	998.8	2200	1081	2380	672.5	97 600	0.1981	0.0078	0.1905	0.0075	0.3886	0.0153	3.54	13.02
	I-28	862.6	1900	1108	2440	580.1	84 200			0.1727	0.0068			3.36	12.38
	I-29	919.4	2025	1103	2430	609.4	88 450	0.1905	0.0075	0.1778	0.0070	0.3683	0.0145	3.43	12.64
	I-30	998.8	2200	1544	3400	660.4	95 850	0.1981	0.0078	0.1829	0.0072	0.3810	0.0150	3.62	13.31
	I-S-2-3	962.5	2120	1378	3035	636.6	92 400	0.1981	0.0078	0.2032	0.0080	0.4013	0.0158	3.14	11.55
	Average	892.5	1965		Average	598.2	86 820						Average	3.52	12.96

NOTE: Specimens with data in parenthesis ( ) were not tested to damage, therefore, these data were not used to determine the averages recorded.

TABLE IV. STATIC PIN BEARING TEST RESULTS - TENSION MODE (CONTINUED)

Specimen Group and Type	Specimen No.	Initial Damage Load		Ultimate Load		Bearing Stress at Damage Load		Deflection						Slope (Bearing Stress/Deflection)	
								Initial		Damage		Total			
		kg	Pound	kg	Pound	MPa	psi	mm	in.	mm	in.	mm	in.	MPa/mm x 10^{-3}	psi/in. x 10^{-6}
Group II t=3.05 mm (0.120 in.) Environmental 355.4 K (180°F) moist air															
Baseline	II-1	839.9	1850	862.6	1900	564.4	81 910	0.0635	0.0025	0.1702	0.0067	0.2337	0.0092	3.32	12.22
	II-2	760.4	1675	805.8	1775	513.1	74 470	0.0686	0.0027	0.1219	0.0048	0.1905	0.0075	4.13	15.52
	II-3	743.1	1650	783.2	1725	499.5	72 500					0.2032	0.0080		
	II-4	737.8	1625	737.8	1625	493.7	71 650	0.0711	0.0026	0.1448	0.0057	0.2159	0.0085	3.41	12.57
	II-5	681.0	1500	721.9	1590	455.4	65 100	0.0711	0.0028	0.1372	0.0054	0.2083	0.0082	3.35	12.35
	II-9	715.0	1575	726.4	1600	478.4	69 440	0.0660	0.0026	0.1118	0.0044	0.1778	0.0070	4.29	15.78
	II-10	(703.7)	(1550)			(406.0)	(58 920)	0.0584	0.0023	(0.1321)	(0.0052)	(0.1905)	(0.0075)	2.50	(9.19)
	II-S	(567.5)	(1250)	(669.6)	(1475)	(379.7)	(55 114)	0.0127	0.0005	(0.1581)	(0.0078)	(0.2108)	(0.0083)	1.92	(7.07)
	Average	747.2	1645		Average	500.8	72 680						Average	3.72	13.69
Chipout	II-11	625.0	1375	1159.1	2550	415.1	60 200	0.0762	0.0030	0.0787	0.0031	0.1549	0.0061	5.28	19.42
	II-12	590.9	1300	1131.8	2490	400.6	58 100	0.0812	0.0032	0.0914	0.0036	0.1727	0.0068	4.38	16.14
	II-13	568.2	1250	1181.8	2600	378.5	54 900	0.0711	0.0028	0.1016	0.0040	0.1372	0.0054	3.73	13.73
	II-14	556.8	1225	1181.8	2600	377.8	54 800	0.0406	0.0016	0.0934	0.0037	0.1346	0.0053	4.03	14.81
	II-15	568.2	1250	1254.6	2760	382.0	55 400	0.0787	0.0031	0.0965	0.0038	0.1524	0.006	3.96	14.58
	Average	581.8	1280		Average	390.9	56 700						Average	4.27	15.73

NOTE: Specimens with data in parenthesis ( ) were not tested to damage, therefore, these data were not used to determine the averages recorded.

TABLE IV. STATIC PIN BEARING TEST RESULTS - TENSION MODE (CONCLUDED)

Specimen Group and Type	Specimen No.	Initial Damage Load		Ultimate Load		Bearing Stress at Damage Load		Deflection						Slope (Bearing Stress/Deflection)	
								Initial		Damage		Total			
		kg	Pound	kg	Pound	MPa	psi	mm	in.	mm	in.	mm	in.	MPa/mm x 10^{-3}	psi/in. x 10^{-6}
Group III thickness effect t=4.32 mm (0.170) Dry															
Baseline	III-1	1212	2670	1734	3820	569.2	82 610	0.1300	0.0051	0.1397	0.0055	0.2692	0.0106	4.08	15.02
	III-2	1167	2570	1530	3370	541.6	78 600	0.0813	0.0032	0.1270	0.0050	0.2083	0.0082	4.27	15.72
	III-3	1203	2650	1544	3400	558.4	81 050	0.0940	0.0037	0.1473	0.0058	0.2413	0.0095	3.79	13.97
	III-4	1203	2650	1476	3250	558.4	81 050	0.1194	0.0047	0.1270	0.0050	0.2464	0.0097	4.40	16.21
	III-5	1221	2690	1530	3370	566.5	82 220	0.1143	0.0045	0.1397	0.0055	0.2540	0.0100	4.06	14.96
	III-6	1126	2480	Not Determined		531.8	77 190	0.1524	0.0060	0.1143	0.0045	0.2667	0.0105	4.66	17.15
	III-7	1167	2570	Not Determined		548.8	79 650	0.1270	0.0050	0.1270	0.0050	0.2540	0.0100	4.29	15.81
	III-8	(1022)	(2250)	Not Determined		(475.5)	(69 010)	0.0889	0.0035	(0.1143)	(0.0045)	(0.2032)	(0.0090)	(4.17)	(15.34)
	Average	1185	2610		Average	553.5	80 340					Average		4.28	15.74
Chipout	III-11	975.1	2150	1135	2500	465.3	67 530	0.0940	0.0037	0.1219	0.0048	0.2159	0.0085	3.82	14.07
	III-12	1090	2400	1239	2730	517.0	75 030	0.0787	0.0031	0.1448	0.0057	0.2235	0.0088	3.57	13.16
	III-13	1248	2750	1416	3120	588.1	85 360	0.0965	0.0038	0.1397	0.0055	0.2362	0.0093	4.21	15.52
	III-14	1112	2450	1317	2900	521.2	75 650	0.1194	0.0047	0.0991	0.0039	0.2184	0.0086	5.27	19.40
	III-15	1282	2825	1330	2930	611.4	88 740	0.1219	0.0048	0.1575	0.0062	0.2794	0.0110	3.69	14.31
	Average	1142	2515		Average	540.6	78 462					Average		4.15	15.29

NOTE: Specimens with data in parenthesis ( ) were not tested to damage, therefore, these data were not used to determine the averages recorded.

TABLE V. - STATIC PIN BEARING TEST RESULTS - COMPRESSION MODE

Specimen Group and Type	Specimen No.	Initial Damage Load		Ultimate Load		Bearing Stress at Damage Load		Deflection						Slope (Bearing Stress/Deflection)	
								Initial		Damage		Total			
		kg	pound	kg	pound	MPa	psi	mm	in.	mm	in.	mm	in.	MPa/mm x 10^{-3}	psi/in. x 10^{-6}
Group I t = 3.05 mm (0.120 in.) Dry															
Baseline	I-9	(794.5	(1750)	Not Determined		(540.6)	(78 470)	0.025	0.0010	(0.183)	(0.0072)	(0.208)	(0.0082)	(2.96)	(10.90)
	I-10	(794.5)	(1750)	Not Determined		(531.6)	(77 160)	0.102	0.0040	(0.193)	(0.0076)	(0.295)	(0.0116)	(2.76)	(10.15)
Chipout	I-17	590.2	1300	817.2	1800	391.0	56 755	0.013	0.0005	0.068	0.0027	0.081	0.0032	5.71	21.02
	I-18	658.3	1450	730.9	1610	439.8	63 831	0.005	0.0002	0.114	0.0045	0.119	0.0047	3.85	14.18
	I-19	(567.5)	(1250)	Not Determined		Not Determined		0.015	0.0006	(0.071)	(0.0028)	(0.086)	(0.0035)		
Delamination	I-S1-2	726.4	1600	776.3	1710	506.4	73 500					0.152	0.0060		
	I-S1-3	737.8	1625	763.2	1725	505.5	73 370					0.147	0.0058		
Oversize	I-S2-4	862.6	1900	1212	2670	569.1	82 600	0.163	0.0072	0.132	0.0052	0.315	0.0124	4.32	15.89
	I-S2-5	726.4	1600	1419	3125	478.2	69 400	0.185	0.0073	0.063	0.0025	0.248	0.0098	7.54	27.77
Group II t = 3.05 mm (0.120 in.) Environmental 355.4 K (180°F) Moist Air															
Baseline	II-6	681.0	1500	737.8	1625	426.4	64 890	0.058	0.0023	0.132	0.0052	0.190	0.0075	3.39	12.48
	II-7	601.6	1325	726.4	1600	404.2	58 670	0.074	0.0029	0.117	0.0046	0.191	0.0075	3.46	12.75
	II-8	681.0	1500	715.0	1575	459.5	66 690	0.030	0.0012	0.198	0.0078	0.228	0.0090	2.01	7.4
Chipout	II-S-62	658.2	1450	1226	2700	440.9	63 900	0	0	0.152	0.006	0.152	0.006	2.89	10.65
	II-S-63	669.6	1475	1271	2800	447.1	64 800	0	0	0.127	0.005	0.127	0.005	3.52	12.96

NOTE: Specimens with data in parenthesis ( ) were not tested to damage

TABLE VI. CYCLIC PIN BEARING TEST DATA ON 3.05 mm (0.120 in.) THICK SPECIMENS

Specimen Hole Type	Specimen Identification	Test Environment	Test Load (R = -1.0, f = 1 Hz) kg	Test Load (R = -1.0, f = 1 Hz) Pounds	Cycles to Failure(1)
Baseline High Quality	I-31	Dry Air	±340.5	±750	2 700(2)
	I-34				251 000 N.F.
	I-35				195 000 N.F.
	I-92				200 000 N.F.
	I-82		±397	±875	210 000 N.F.
	I-83				80 000
	I-86				215 000 N.F.
	I-87				187 000 N.F.
	I-91				217 000 N.F.
	I-39		±454	±1000	195 000 N.F.
	I-89				60 000
	I-90				190 000 N.F.
Chipout	I-42	Dry Air	±397	±875	29 000
	I-43				42 000
	I-45				13 000
	I-46				40 500
	I-50				210 000 N.F.
	I-66				210 000 N.F.
	I-70				103 000
	I-71				191 700
	I-51R				51 000
	I-52R				26 [illegible]
	I-53R				50 000

(1) Failure defined as the number of cycles at which the pin deflection reaches 140% of initial pin deflection.

(2) Specimen I-31 only tested until pin deflection reached 125% of initial pin deflection.

TABLE VI. CYCLIC PIN BEARING TEST DATA ON 3.05 mm (0.120 in.) THICK SPECIMENS (CONTINUED)

Specimen Hole Type	Specimen Identification	Test Environment	Test Load (R = -1.0, f = 1 Hz)		Cycles to Failure[1]
			kg	Pounds	
Chipout (con't'd)	I-47	Dry Air	±454	±1000	3 300
	I-48				45 000
	I-49				98 000
	I-65				27 000
	I-68				63 000
	I-69				130 000
Oversize	I-58		±397	±875	185 000 N.F.
	I-59				84 000
	I-60				50 000
	I-64				200 000 N.F.
	I-61		±454	±1000	7 200
	I-62				32 500
	I-63				65 000
Delamination	I-52	Dry Air	±397	±875	170 000 N.F.
	I-53				152 000
	I-54				200 000 N.F.
	I-55				200 000 N.F.
	I-73				124 000
	I-77				208 000 N.F.
	I-78				205 000 N.F.
	I-56		±454	±1000	196 000 N.F.
	I-57				63 500
	I-72				31 000
	I-74				26 000
	I-75				39 000
	I-76				104 000

(1) Failure defined as the number of cycles at which the pin deflection reaches 140% of initial pin deflection.

TABLE VI. CYCLIC PIN BEARING TEST DATA ON 3.05 mm (0.120 in.) THICK SPECIMENS (CONCLUDED)

Specimen Hole Type	Specimen Identification	Test Environment	Test Load (R = -1.0, f = 1 Hz)		Cycles to Failure(1)
			kg	Pounds	
Baseline High Quality	II-16	Hot Moist Air	±397	±875	6 000
	II-17				82 000
	II-19				68 000
Chipout	II-22				90 000
	II-23				500
	II-24				5 500
	II-25				300
	II-27R				15 000
	II-28R				31 000
	II-29R				95 000

(1) Failure defined as the number of cycles at which the pin deflection reaches 140% of the initial pin deflaction.

TABLE VII. CYCLIC PIN BEARING TEST DATA ON 4.32 mm (.170 in.) THICK SPECIMENS

Specimen Hole Type	Specimen Identification	Test Environment	Test Load (R = -1.0, f = 1 Hz) kg	Pounds	Cycles to Failure(1)
Baseline High Quality	III-16	Dry Air	±568	±1250	80 000
	III-17				41 500
	III-18				200 000 N.F.
	III-19				200 000 N.F.
Chipout	III-21				205 000 N.F.
	III-22				205 000 N.F.
	III-23				230 000 N.F.
	III-24				205 000 N.F.
	III-25				210 000 N.F.
	III-26				200 000 N.F.
Double Chipout	III-S-7-5				129 000
Thicker Double Chipout	III-S-7-4				65 000

(1) Failure defined as the number of cycles at which the pin deflection reaches 140% of the initial pin deflection.

TABLE VIII. STATIC COMPRESSION TEST DATA

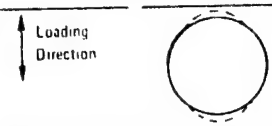
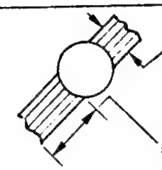
Specimen Type(1) Identification	Ultimate Compression (2) Load N x 10^3	Ultimate Compression (2) Load lb	Ultimate Compression (2) Strength MPa	Ultimate Compression (2) Strength ksi	Ultimate Compression (2) Strain (Head Movement) mm	Ultimate Compression (2) Strain (Head Movement) in.	Slope (Compression Strength/Strain) MPa/mm x 10^{-3}	Slope (Compression Strength/Strain) ksi/in. x 10^{-3}
No Hole								
1	44.26	9,950	565.39	82.0	0.6401	0.0252	0.8808	3.25
2	43.37	9,750	553.67	80.3	0.6299	0.0248	0.8780	3.24
3	41.81	9,400	542.64	78.7	0.6096	0.0240	0.8889	3.28
4	36.92	8,300	471.62	68.4	0.5080	0.0200	0.9268	3.42
5	43.59	9,800	553.67	80.3	0.5893	0.0232	0.9377	3.46
6	41.37	9,300	530.23	76.9	0.5690	0.0224	0.9295	3.43
7	40.47	9,100	519.19	75.3	0.5994	0.0236	0.8645	3.19
8	44.92	10,100	577.11	83.7	0.6706	0.0264	0.8591	3.17
9	42.03	9,450	528.16	76.6	0.5466	0.0216	0.9621	3.55
10(3)	(38.25)	(8,600)	(488.17)	(70.8)	(0.6198)	(0.0244)	0.7859	2.90
Average	42.08	9,461	537.96	78.02	0.5961	0.0235	0.8913	3.28
Hole, Baseline Control								
11	29.27	6,580	374.40	54.3	1.4605	0.0575	0.2559	0.9444
12	28.42	6,390	364.75	52.9	1.3970	0.0550	0.2606	0.9618
13	28.82	6,480	370.26	53.7	1.4605	0.0575	0.2531	0.9339
14	27.91	6,275	359.23	52.1	1.3970	0.0550	0.2567	0.9473
15	28.36	6,375	364.75	52.9	1.4275	0.0562	0.2551	0.9413
16	29.36	6,600	376.47	54.6	1.3970	0.0550	0.2690	0.9927
17	29.13	6,550	378.54	54.9	1.4173	0.0558	0.2666	0.9839
18	29.07	6,535	375.09	54.4	1.4275	0.0562	0.2623	0.9680
19	28.36	6,375	361.99	52.5	1.4275	0.0562	0.2532	0.9342
20(3)	(26.69)	(6,000)	(344.06)	(49.9)	(1.335)	(0.0525)	0.2576	0.9505
Average	28.74	6,462	369.50	53.59	1.4235	0.0560	0.2504	0.9558
Hole, Delamination								
26	28.47	6,400	374.40	54.3	1.4732	0.0580	0.2537	0.9362
27	26.47	5,950	348.89	50.6	1.3411	0.0528	0.2597	0.9583
28	24.13	5,425	312.34	45.3	1.2395	0.0488	0.2516	0.9283
29	26.06	5,860	338.54	49.1	1.3767	0.0542	0.2455	0.9059
30(3)	(22.46)	(5,050)	(291.66)	(42.3)	(1.1303)	(0.0445)	0.2576	0.9506
Average	26.28	5,909	343.54	49.8	1.3576	0.0534	0.2536	0.9336
Hole, Chipout								
31	27.22	6,120	352.34	51.1	1.3081	0.0515	0.2689	0.9922
32	27.58	6,200	359.23	52.1	1.3970	0.0550	0.2567	0.9473
33	27.13	6,100	353.71	51.3	1.3335	0.0525	0.2648	0.9771
34	27.58	6,200	357.85	51.9	1.3665	0.0538	0.2614	0.9647
35	28.02	6,300	366.12	53.1	1.3970	0.0550	0.2616	0.9654
36(3)	(24.91)	(5,600)	(324.76)	(47.1)	(1.2065)	(0.0475)	0.2687	0.9916
Average	27.51	6,184	357.85	51.9	1.3604	0.536	0.2637	0.9730

Notes: (1) Specimens 3.05 mm (0.120 in.) Thick T300/5208 Graphite/Epoxy, Holes 4.83 mm (0.190 in.) dia., Layup $(45, 0, -45, 90_2, -45, 0, 45)_3$, see Figure 2

(2) Compression test strain rate 1.27 mm/minute (0.05 in./min.).

(3) Specimens with data in parenthesis ( ) were not tested to damage, therefore these data were not used to determine the averages recorded.

TABLE IX. GRAPHITE/EPOXY COMPOSITE HOLE ACCEPT/REJECT CRITERIA

Hole Defects	Current Requirements (Lockheed P671 576A)	Size of Deliberate Defects Tested	Proposed Requirements	Reason
Chipout	≤25% of hole or countersunk circumference ≤0.25 mm (0.010 in.) deep max	 40% of hole circumference, 0.38 mm (0.015 in.) deep by 0.33 mm (0.013 in.) wide	Maintain current requirements	Large defects tested showed decreases in static pin bearing strength and decreases in pin bearing endurance characteristics
Delamination	≤0.25 mm (0.010 in.) into hole axially ≤1.78 mm (0.070 in.) beyond hole or countersunk edge	 	For non-compression (buckling) applications reduce requirements permitting single ply delaminations up to 3 diameters in length not wider than 1.78 mm (0.070 in.)	No effect on static pin bearing strength 1 Small effect on pin bearing endurance characteristics. Compressive strength lowered
Size	(Including oversize) for 4.76 mm (3/16 in.) nominal 95% of holes 4.801 to 4.877 mm (0.1630 to 0.1920 in.) diameter, 5% of holes 4.801 to 4.928 mm (0.1890 to 0.1940 in.) provided that no more than two adjacent holes are oversize and no more than 5% of the holes in a pattern of 100 holes are so affected. Holes greater than 4.923 mm (0.1940 in.) diameter shall be increased to the next fastener size	5.004 to 5.029 mm (0.1970 to 0.1980 in.) diameter	Maintain current requirements	Decreased pin bearing endurance characteristics

1 Recommend additional static pin bearing compression tests and cyclic pin bearing tests

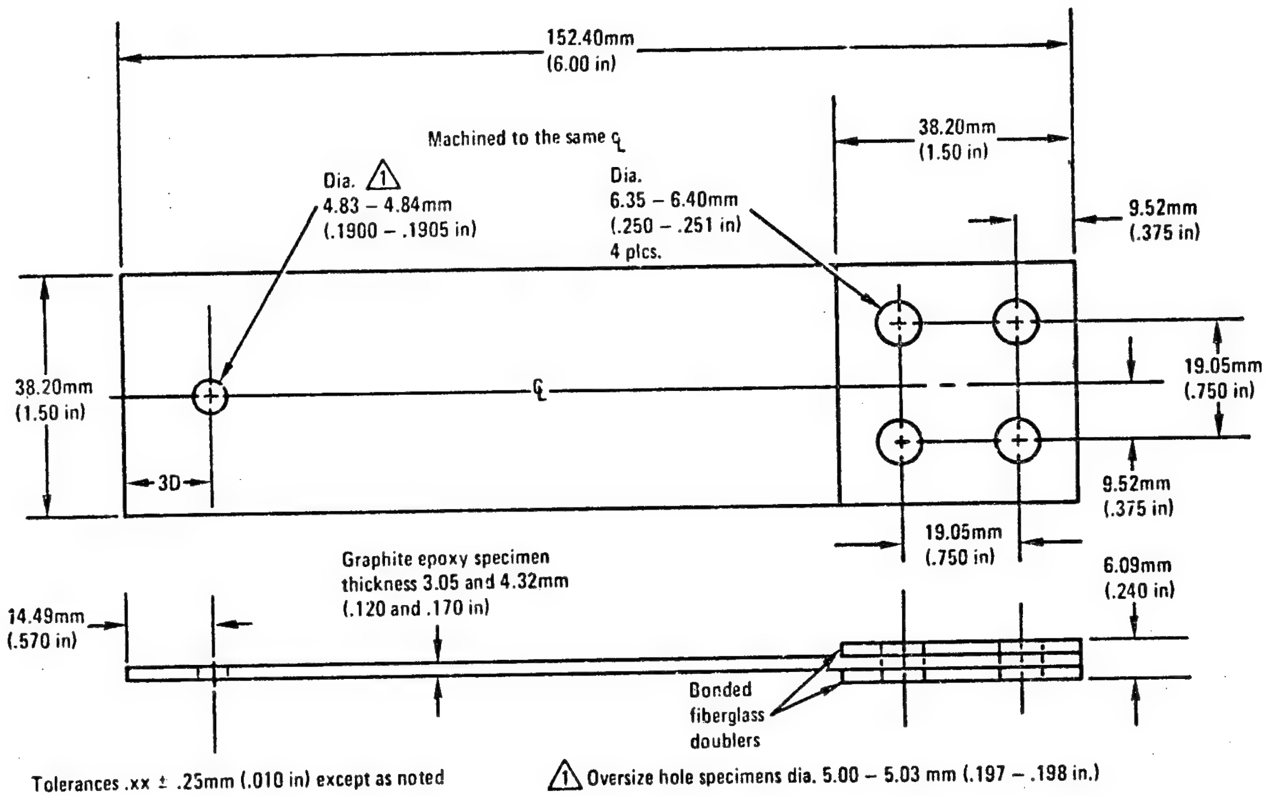
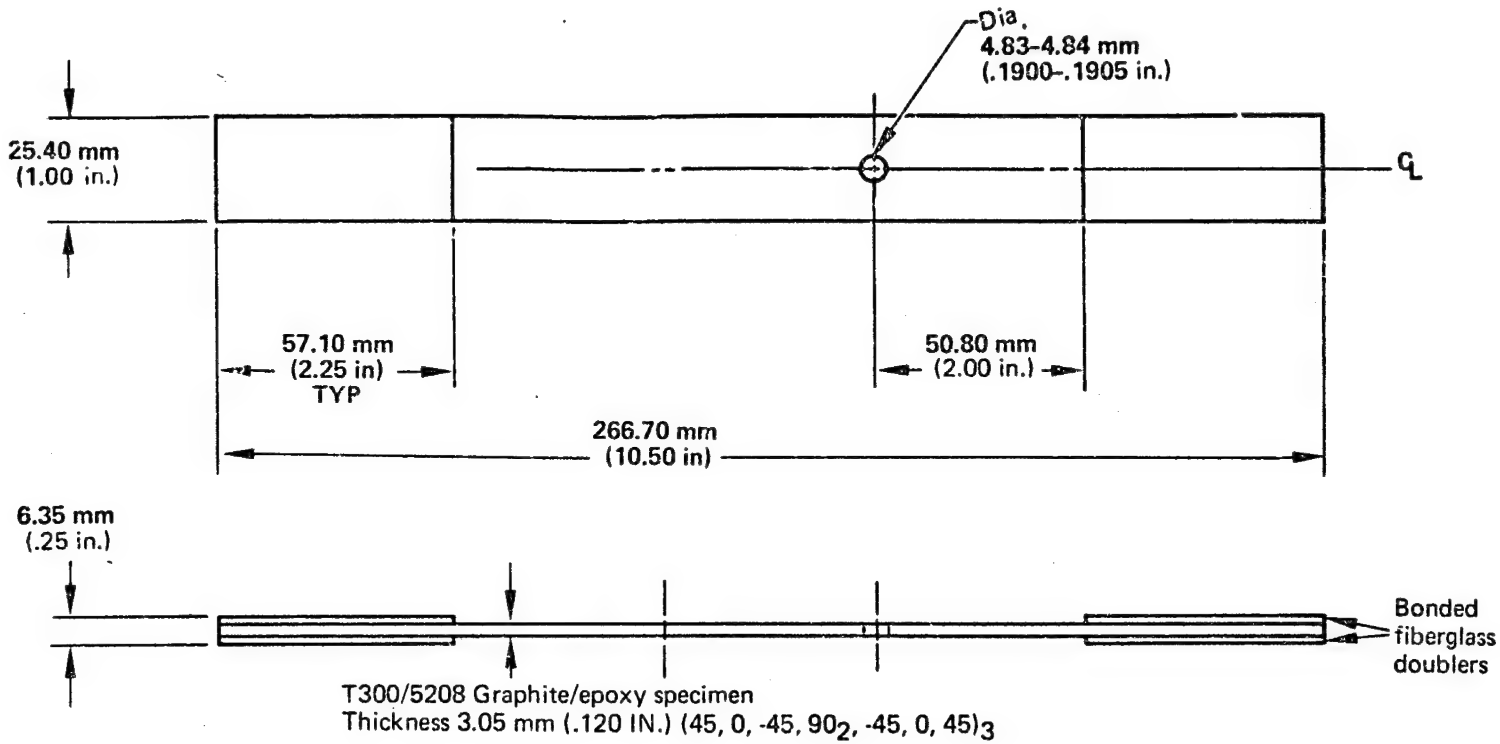


Figure 1. - Static and fatigue pin bearing test specimen configuration.



Tolerances .XX ± .25 mm (.010 in) except as noted

Figure 2. - Compression test specimen configuration.

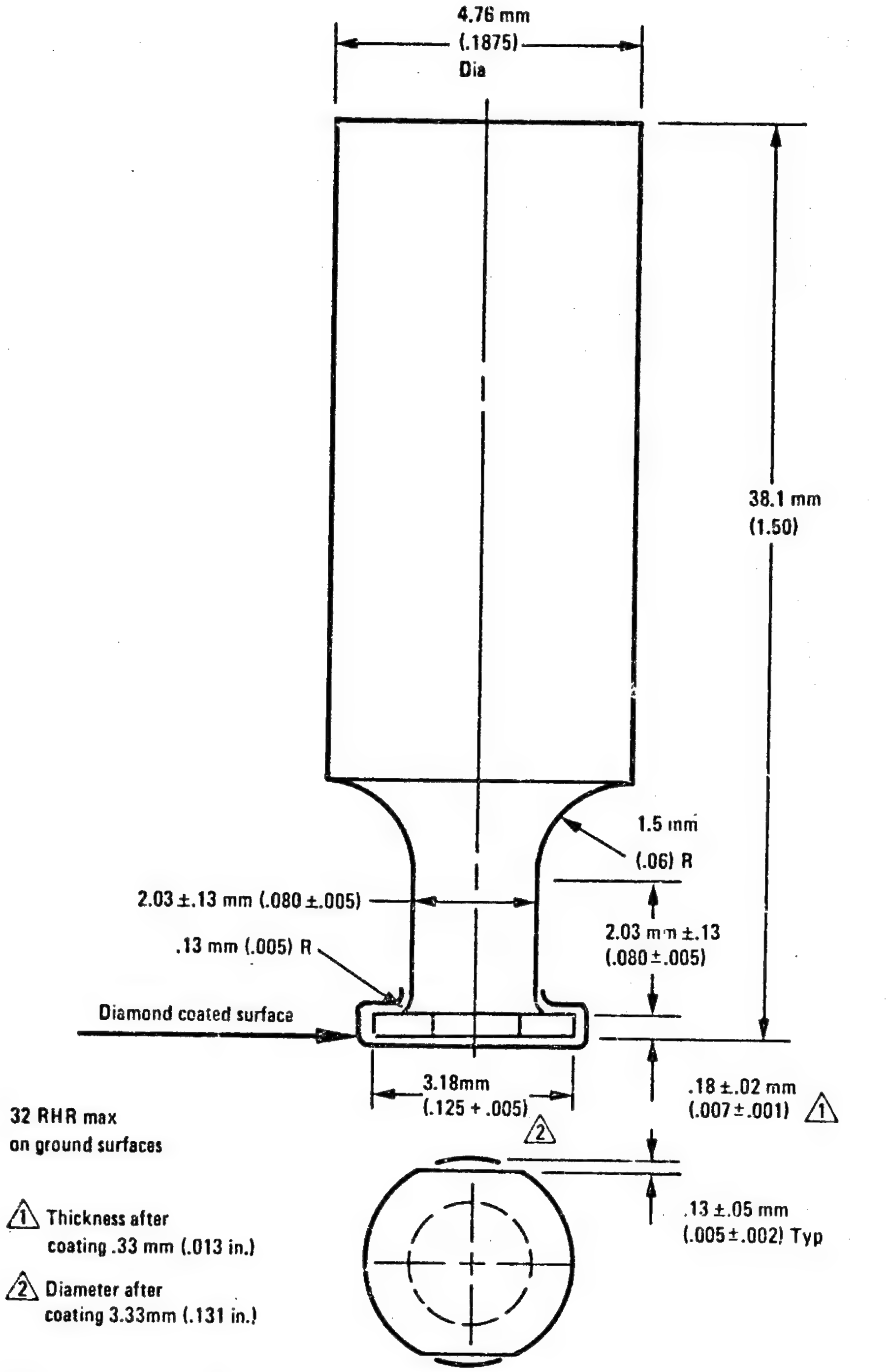


Figure 3. - Diamond coated Woodruff style cutter used to generate Chipout type hole defects.

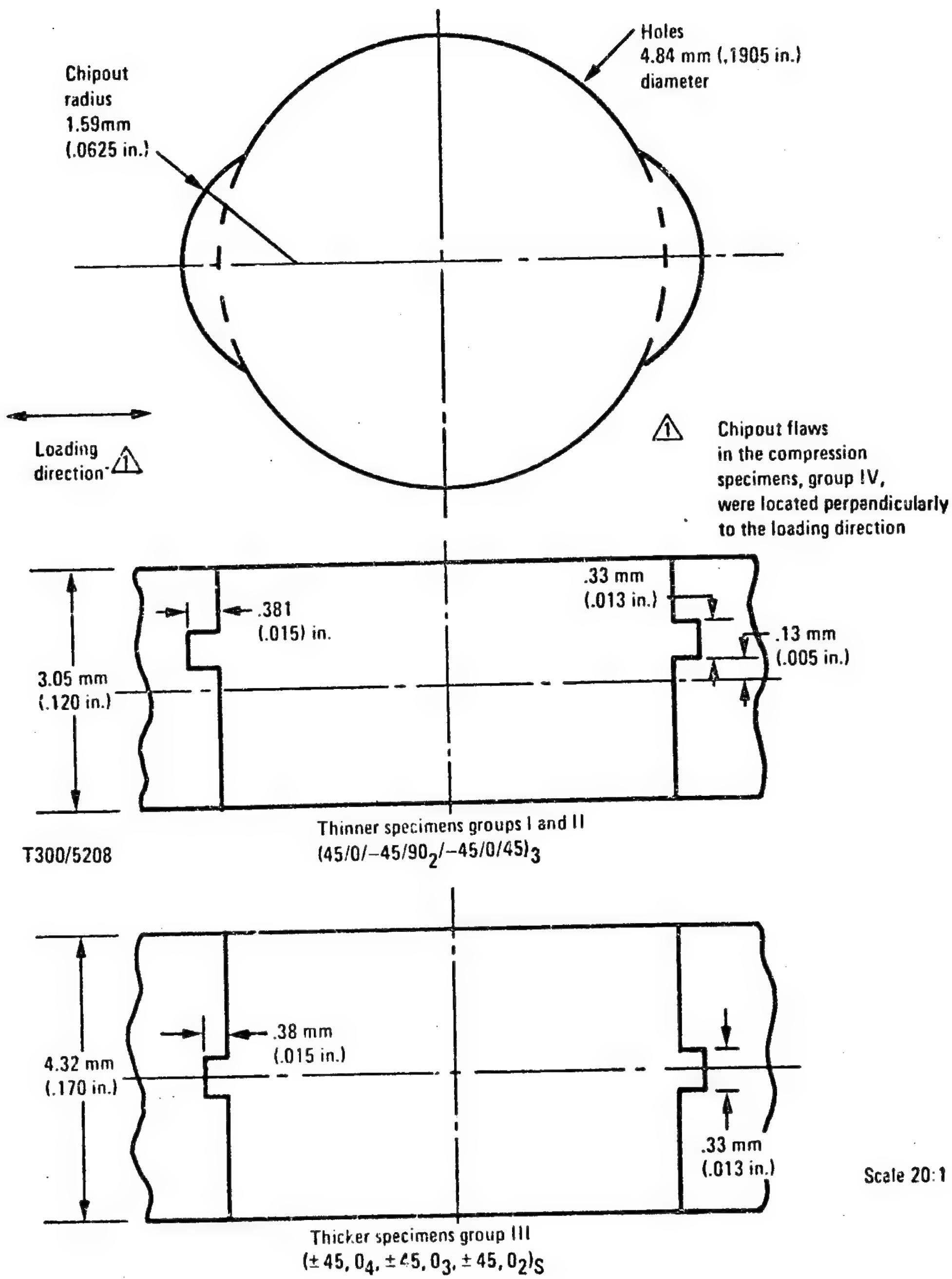


Figure 4. - Schematic diagram of chipout type flawed holes.

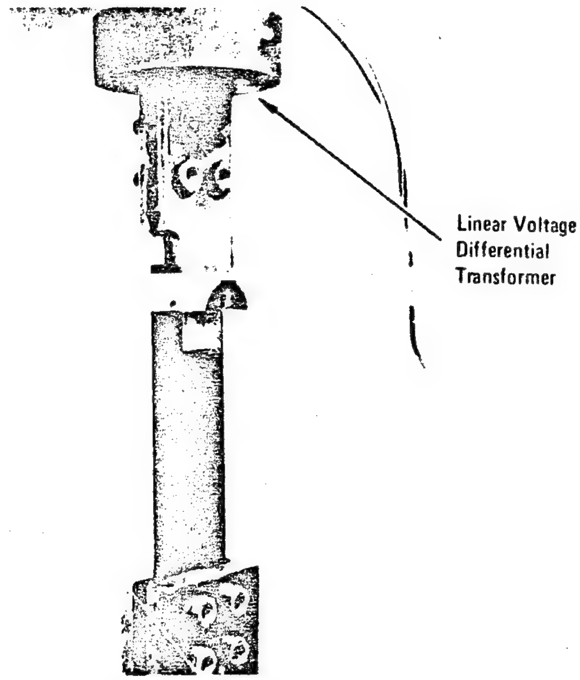


Figure 5. - Photograph of static and cyclic pin bearing test setup.

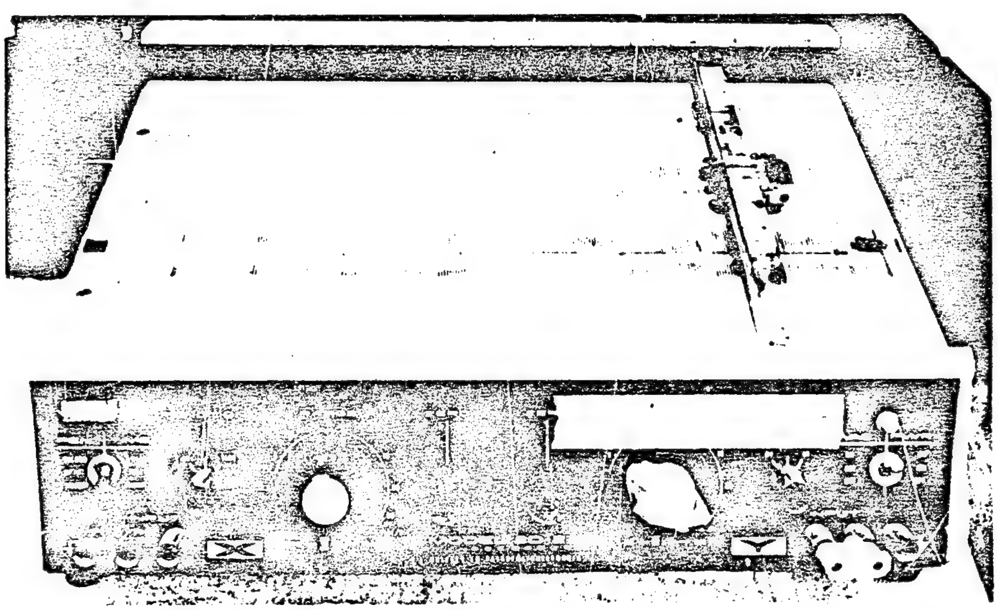


Figure 6. - Photograph of X-Y plotter used to record pin deflection during static and cyclic testing.

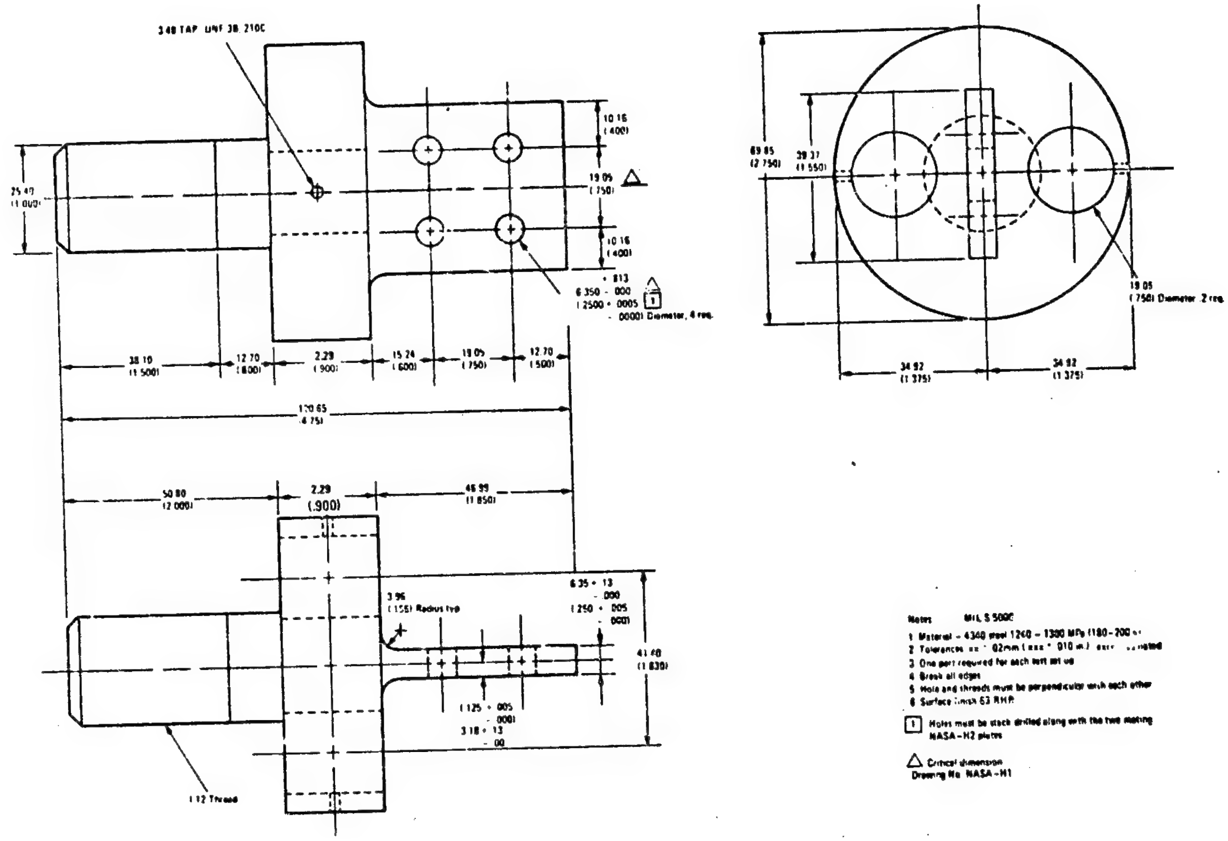


Figure 7. - Upper loading fixture.

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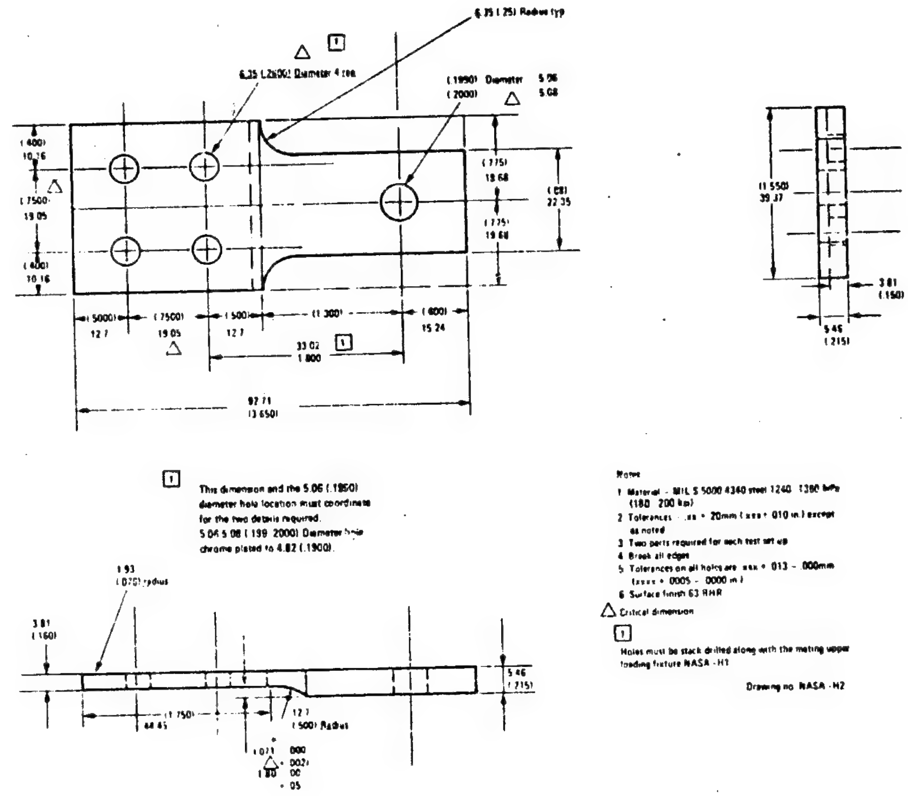


Figure 8. - Upper loading plates.

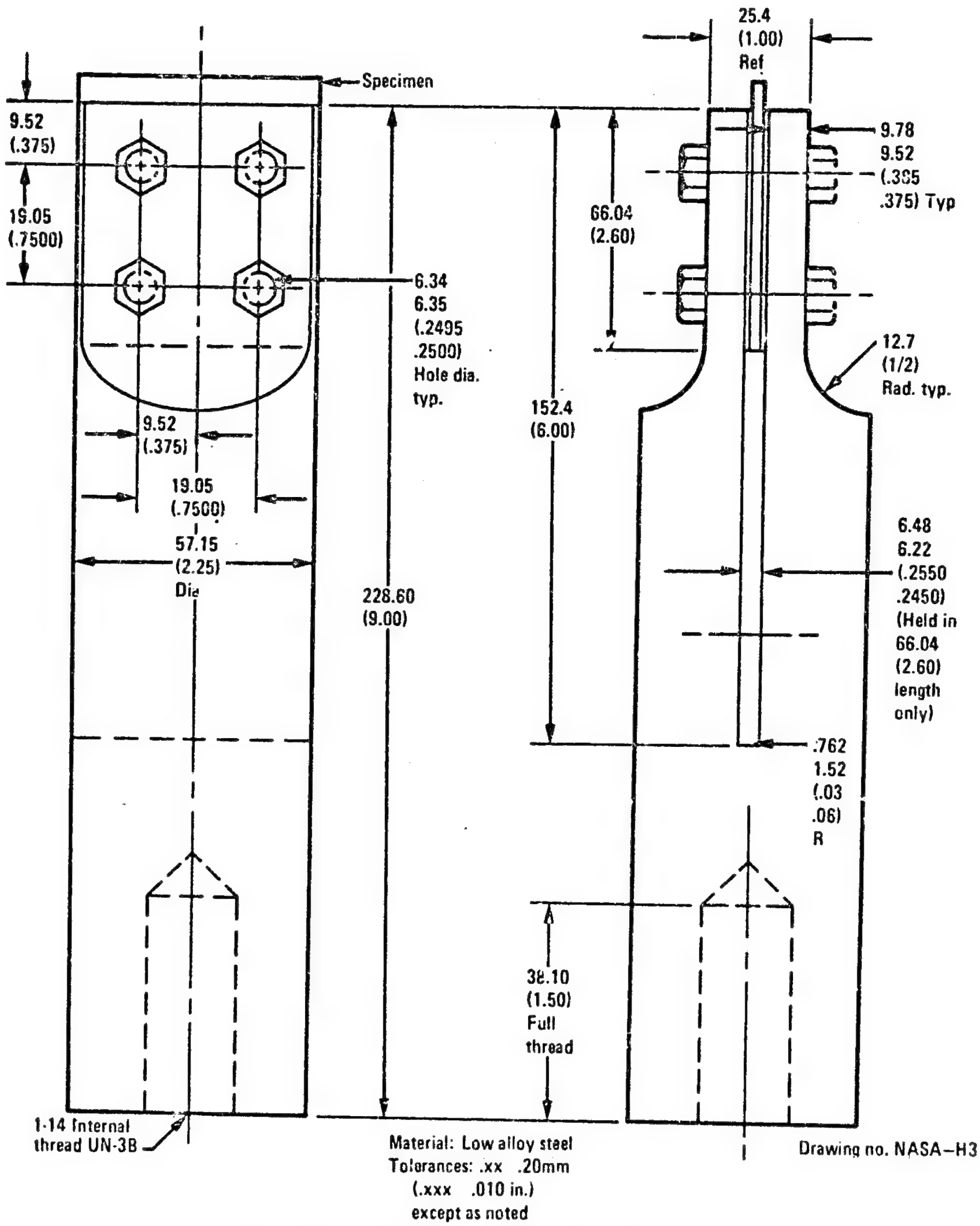


Figure 9. - Lower clevis test fixture.

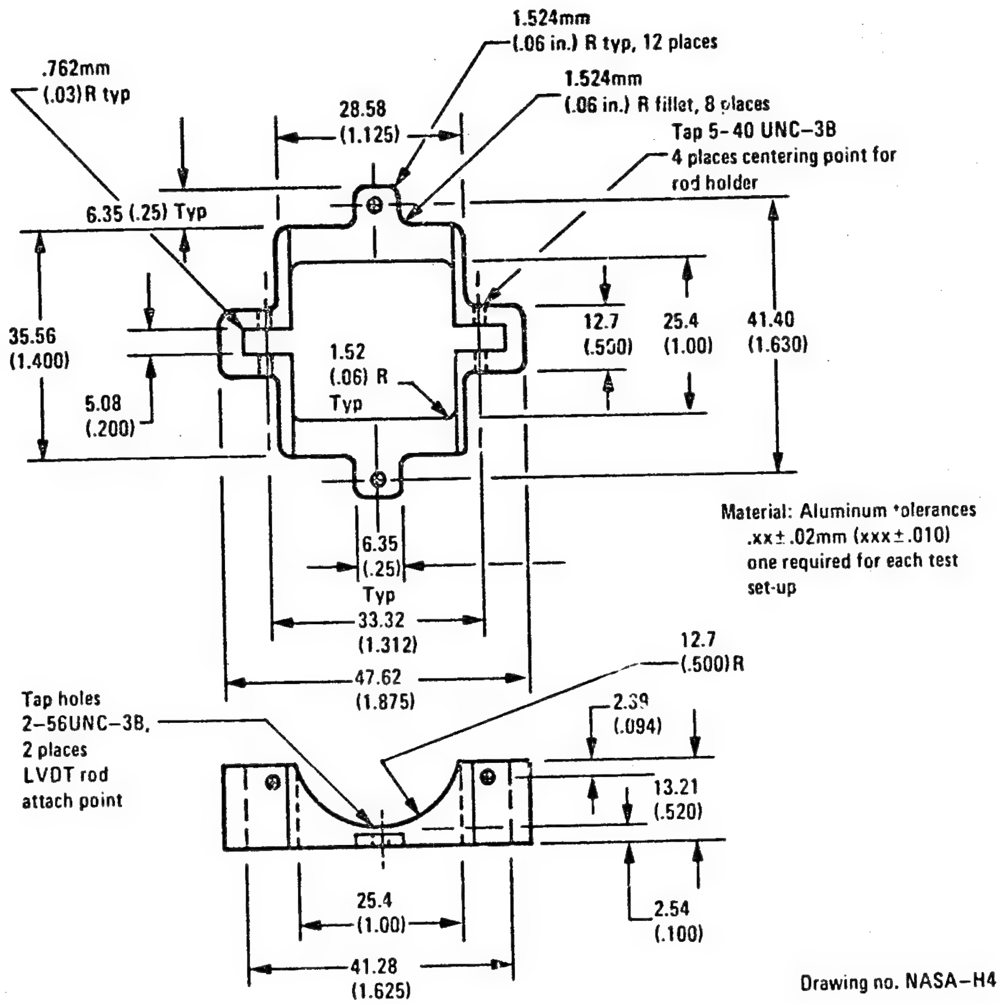
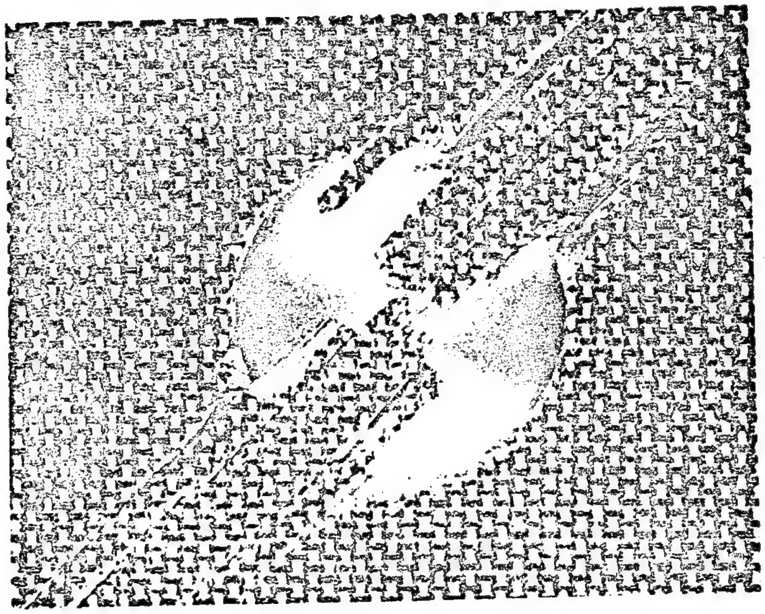


Figure 10. - Linear voltage differential transformer (LVDT) rod holder.



10X

Figure 11. - Typical delamination type defective specimen macrophotograph.

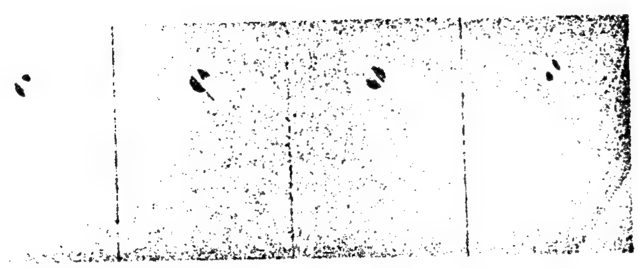


Figure 12. - Exit face of typical delamination type defective specimens.

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Figure 13. - Photopositive of DIB enhanced radiograph of delaminated type defective specimens.

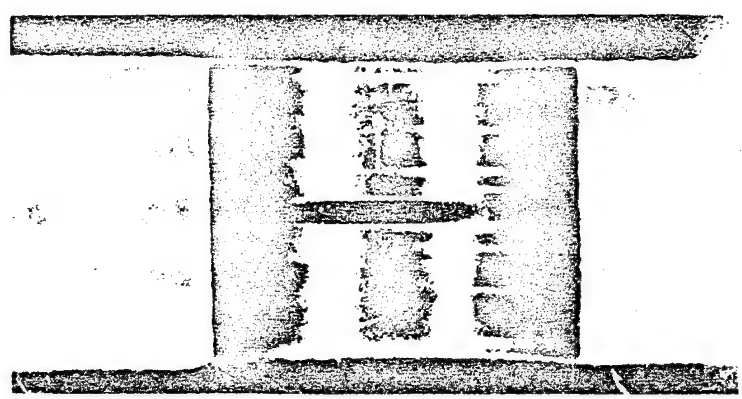

Figure 14. - Macrophotograph of sectioned chipout type defective group III 4.32 mm (0.170 in.) thick specimen.

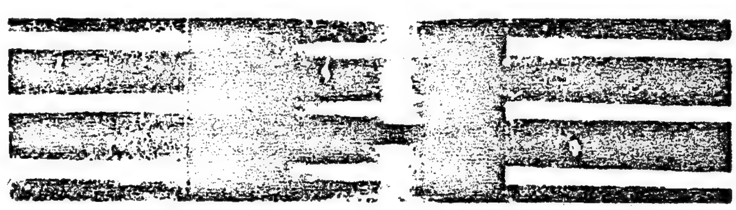

Figure 15. - Macrophotograph of sectioned chipout type defective group I and II 3.05 mm (0.120 in.) thick specimen.

Figure 16. - Photopositive of DIB enhanced radiograph of chipout type defective specimens. Note: Chipout flaw shown as dark area and lighter gray area is from DIB retained on specimen face.

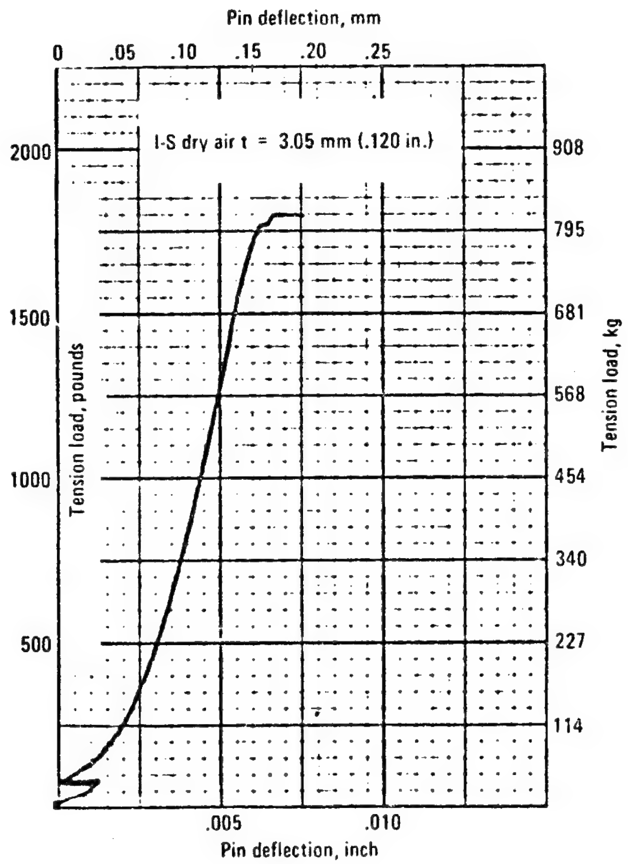

Figure 17.- Typical deflection curve for a tension loaded pin bearing specimen.

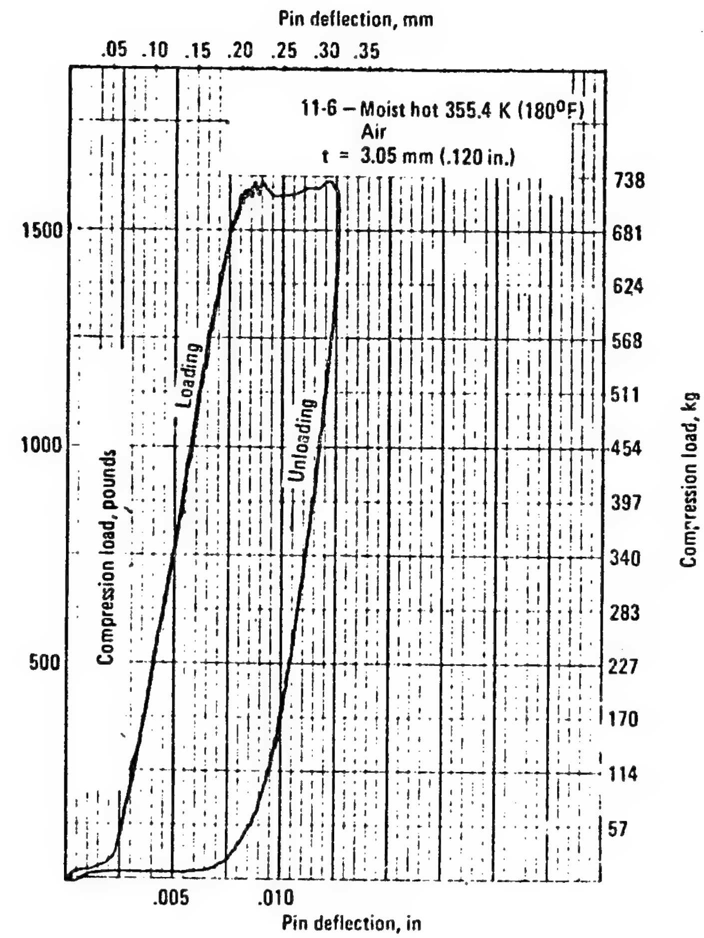

Figure 18. - Typical load deflection curve for a specimen loaded in a pin bearing compression mode.

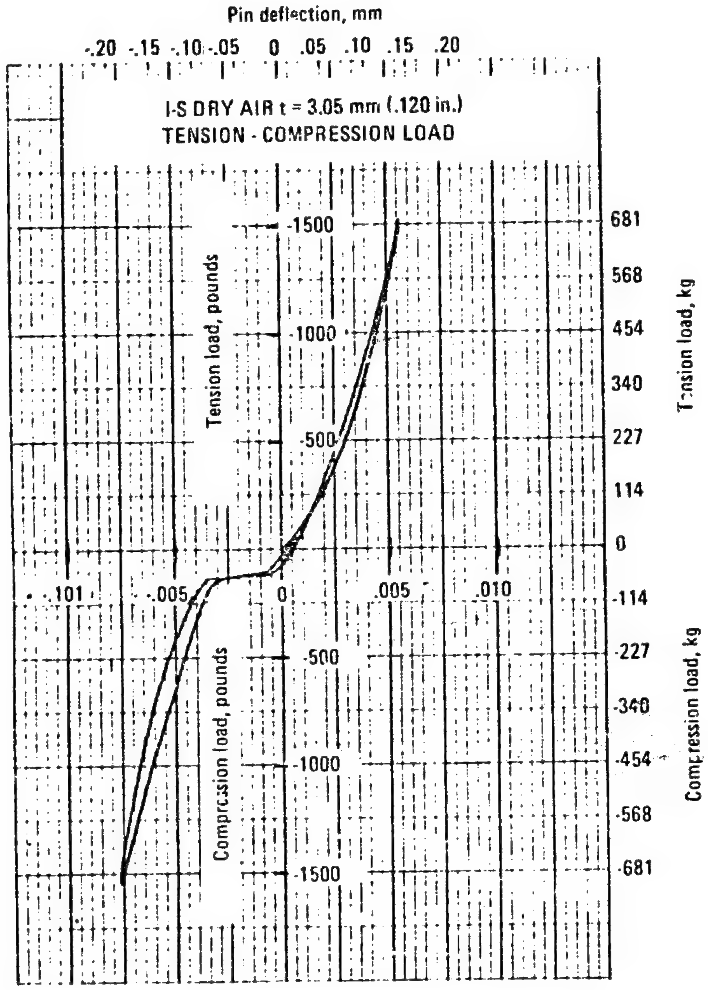

Figure 19. - Load deflection curve for specimen loaded in both tension and compression pin bearing.

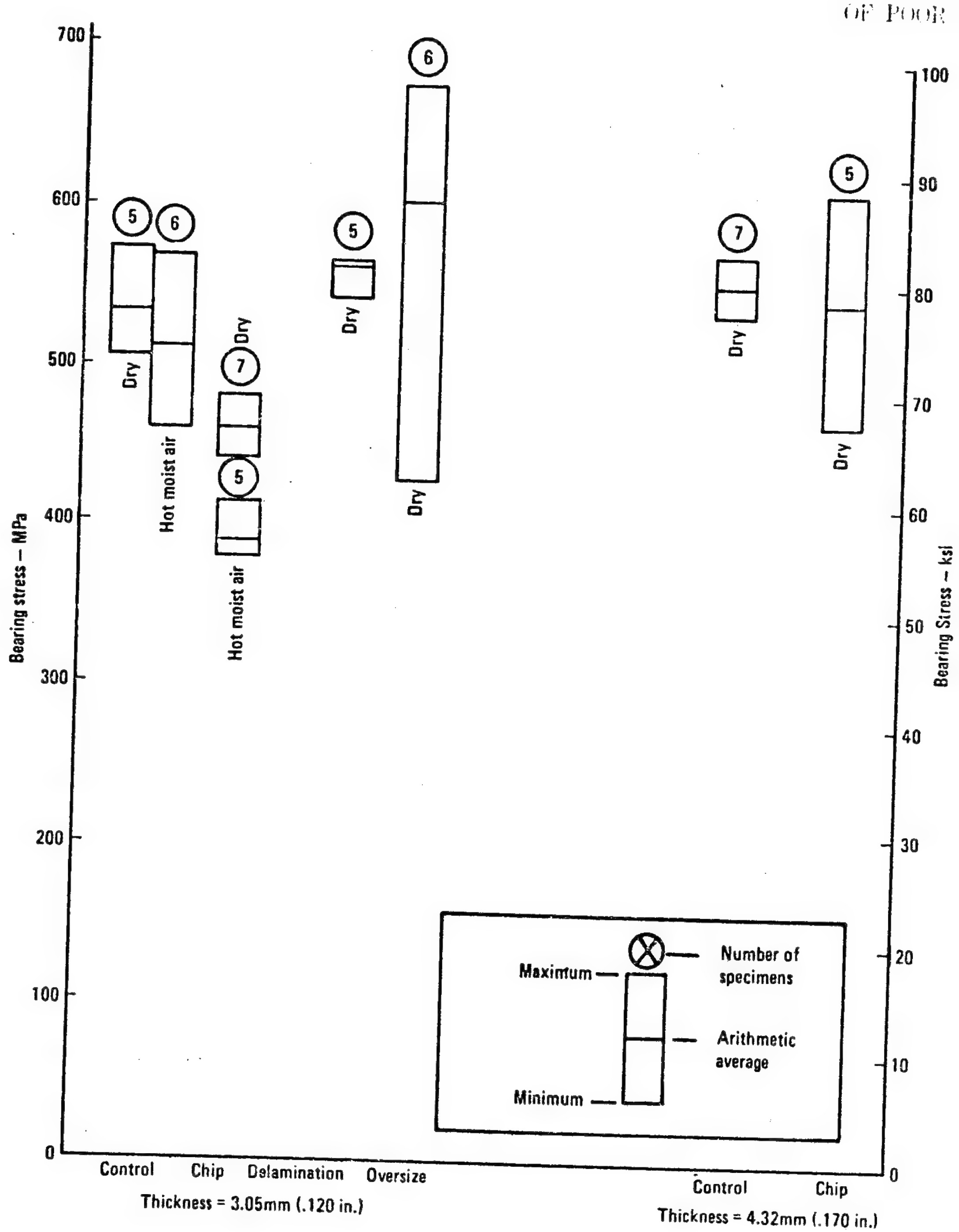

Figure 20. - Summary of static tension pin bearing tests.

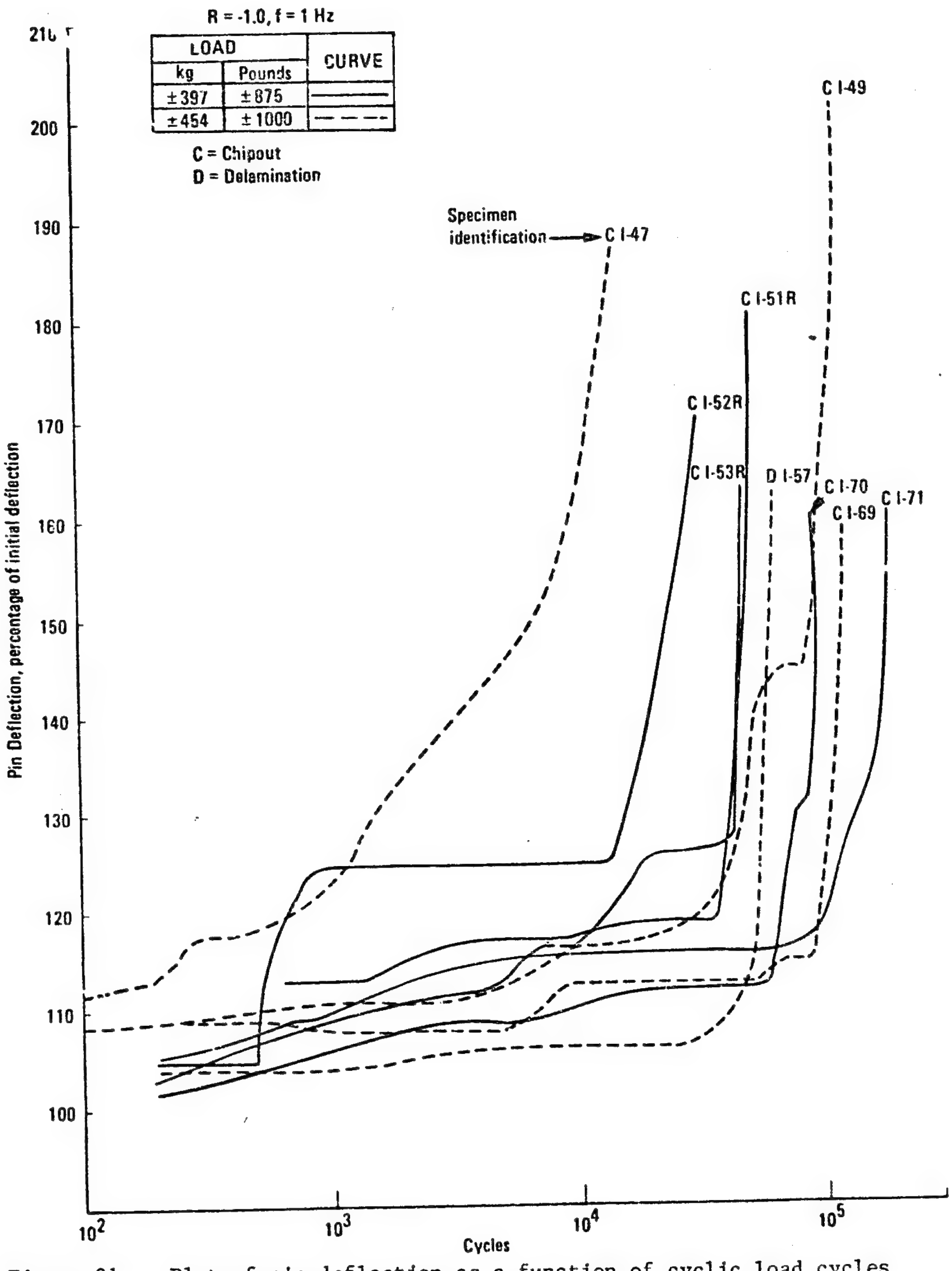

Figure 21. - Plot of pin deflection as a function of cyclic load cycles for specimens tested above 140% initial pin deflection.

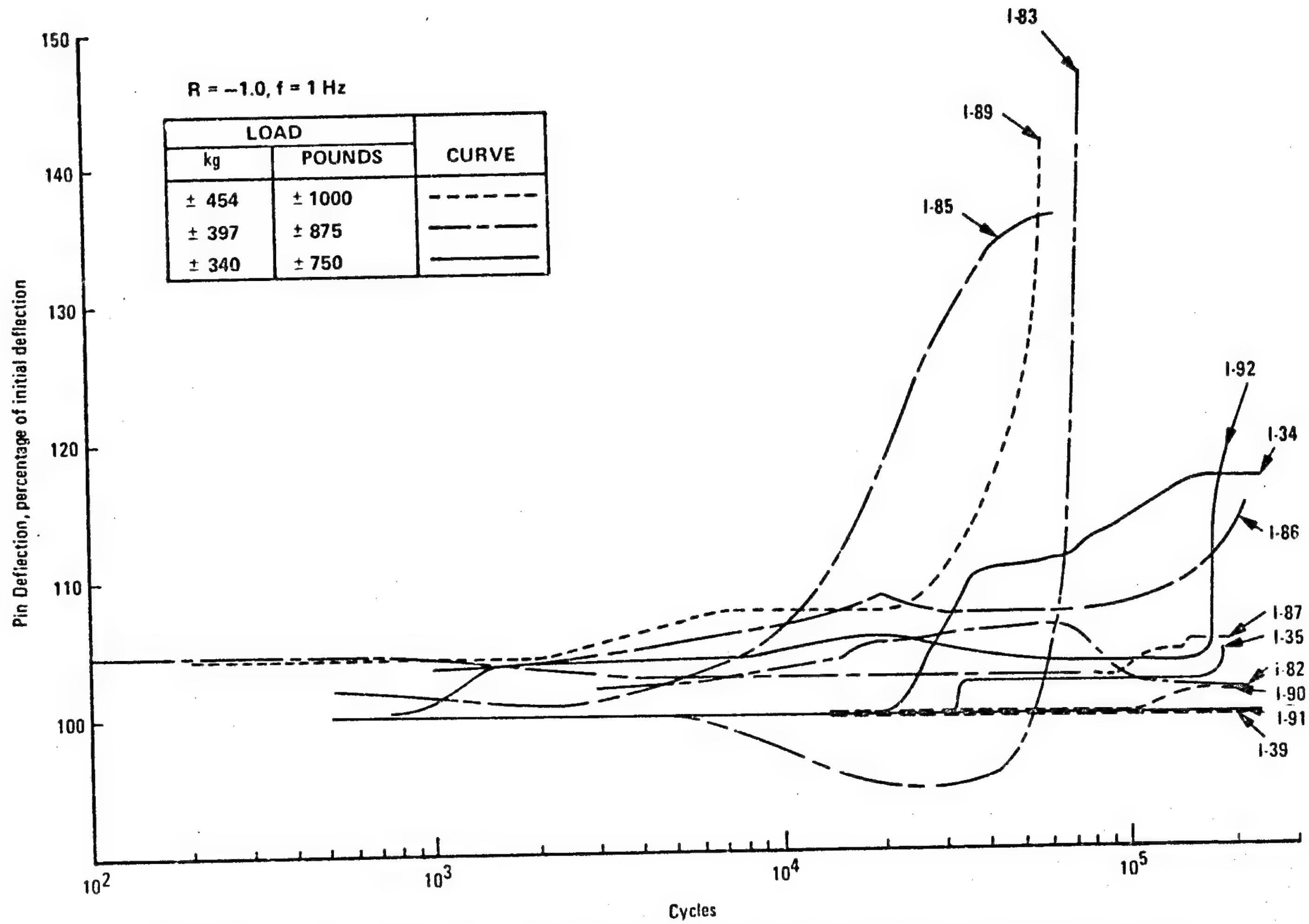

Figure 22. - Pin deflection versus test cycles for baseline high quality specimens tested in dry air.

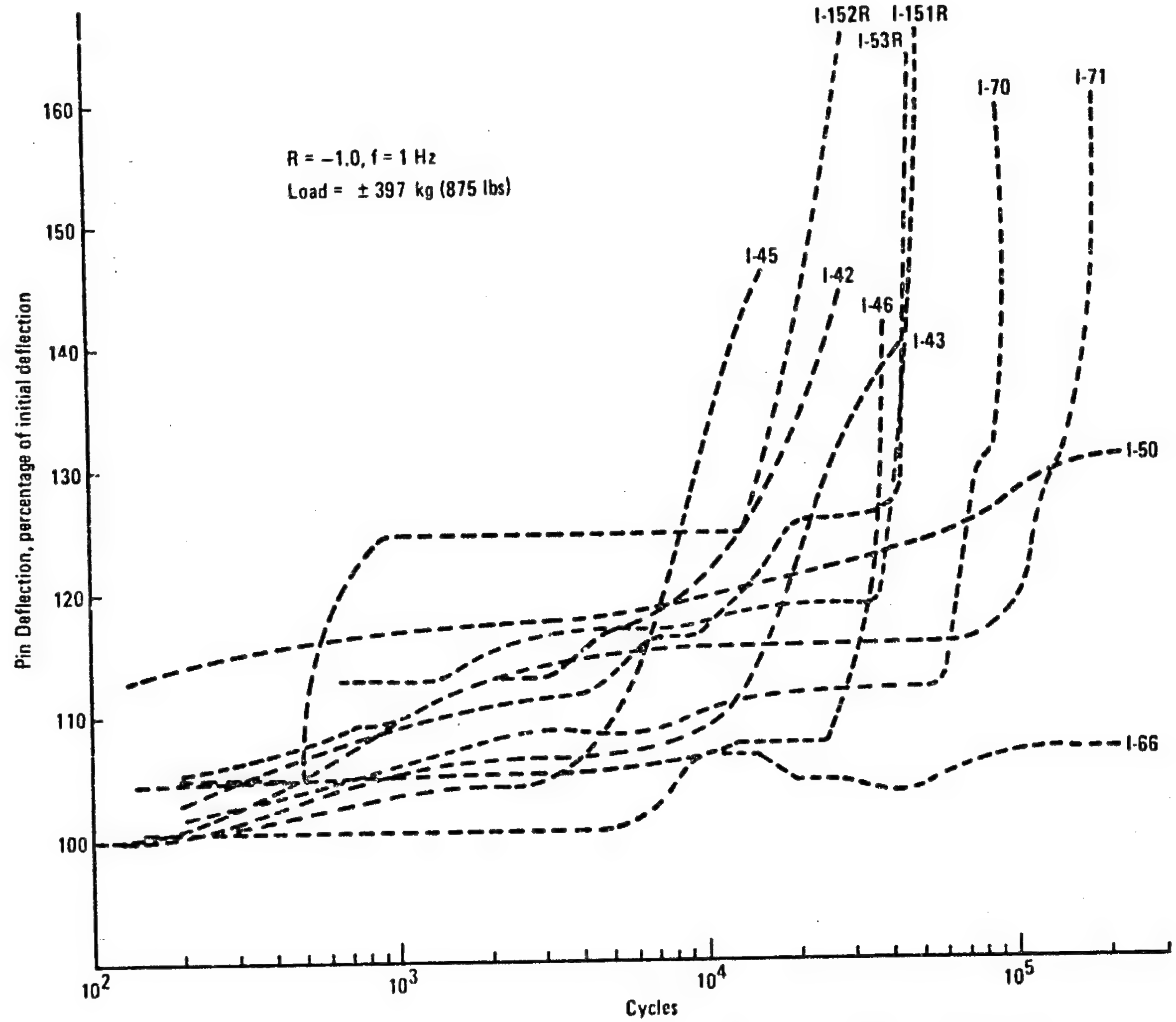

Figure 23. - Pin deflection versus test cycles for chipout specimens tested in dry air.

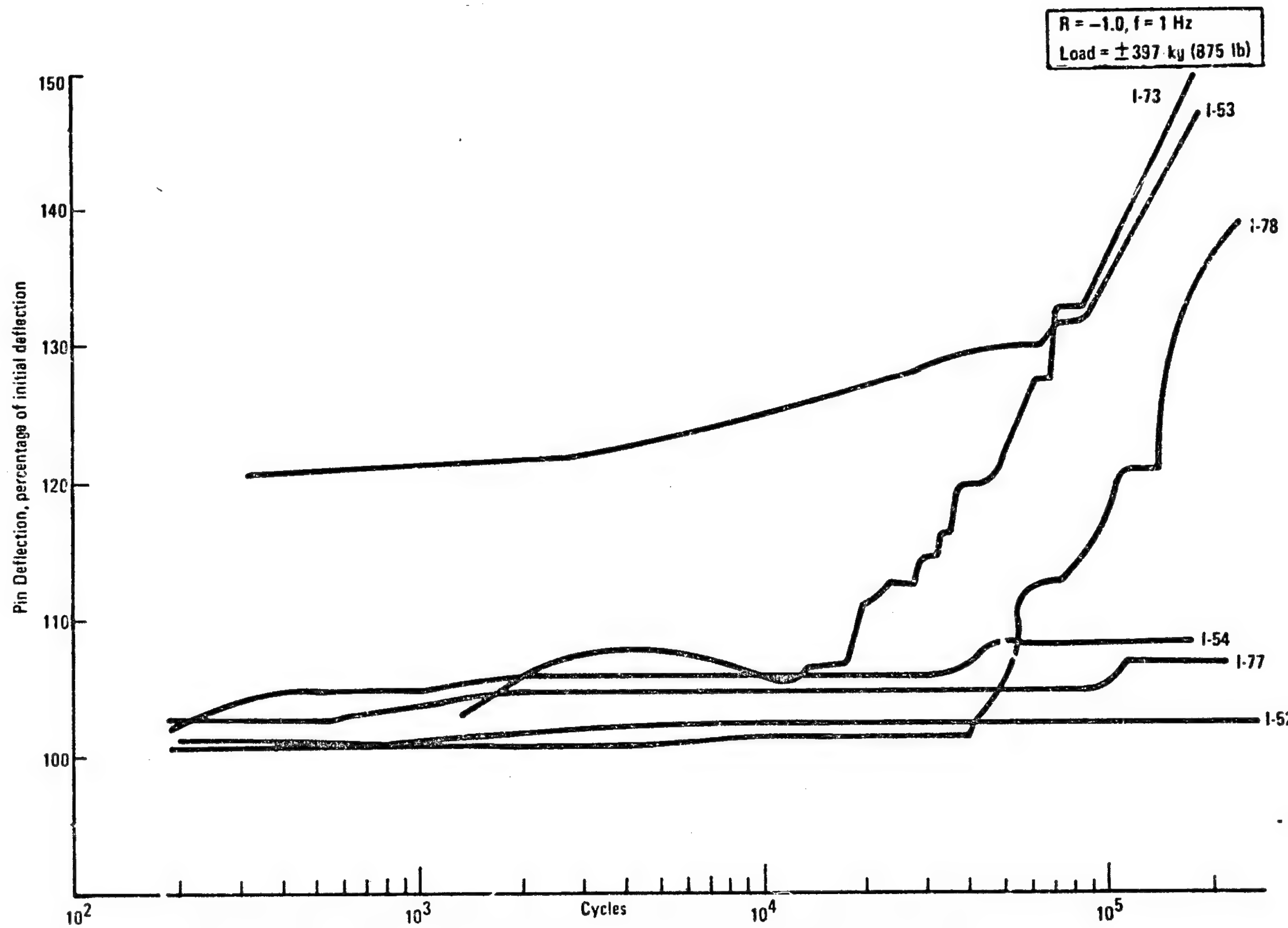

Figure 24. - Pin deflection versus test cycles for delaminated specimens tested in dry air.

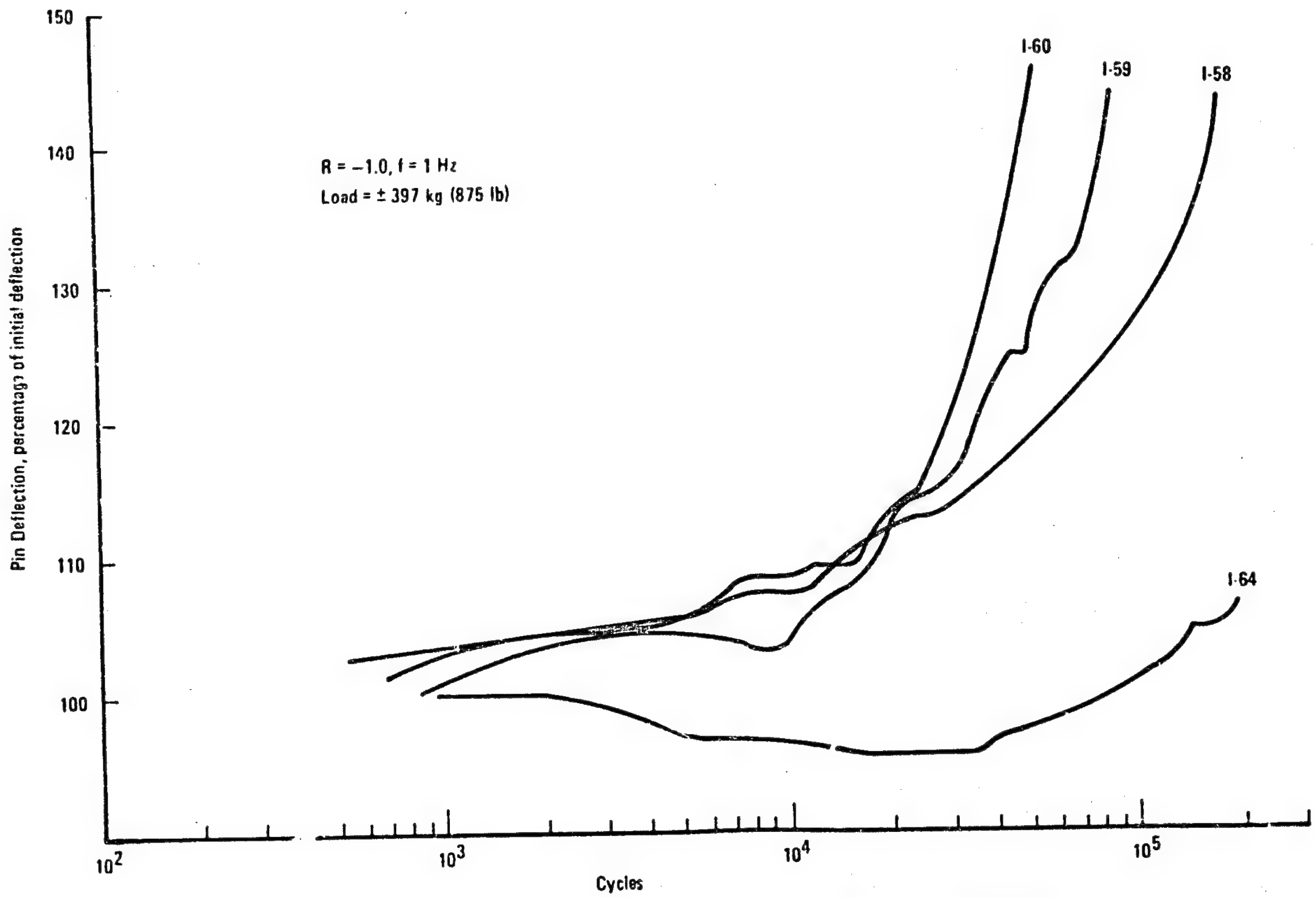

Figure 25. - Pin deflection versus test cycles for oversized hole specimens tested in dry air.

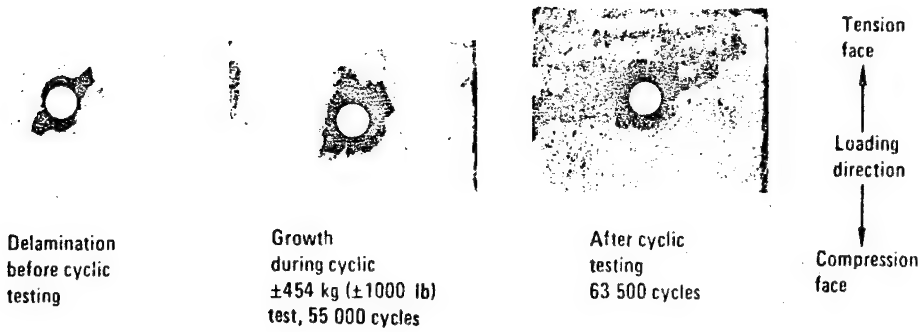

Figure 26. - Photopositives of DIB enhanced radiographs of delamination defective specimen, I-57, before, during, and after cyclic pin bearing testing.

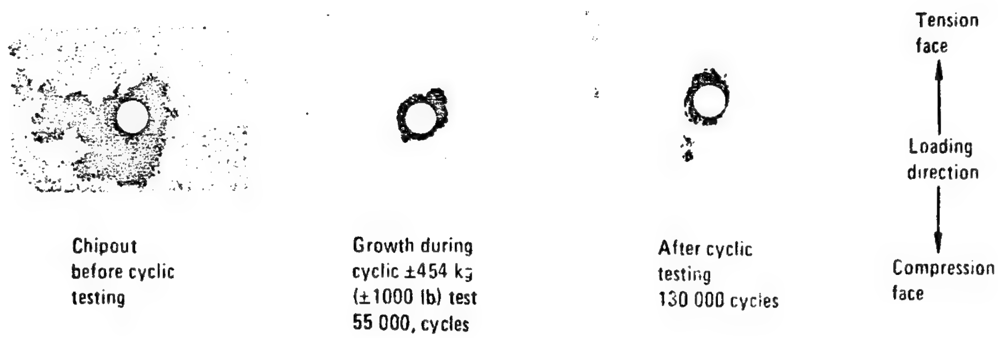

Figure 27. - Photopositives of DIB enhanced radiographs of chipout defective specimen, I-69, before, during, and after cyclic pin bearing testing.

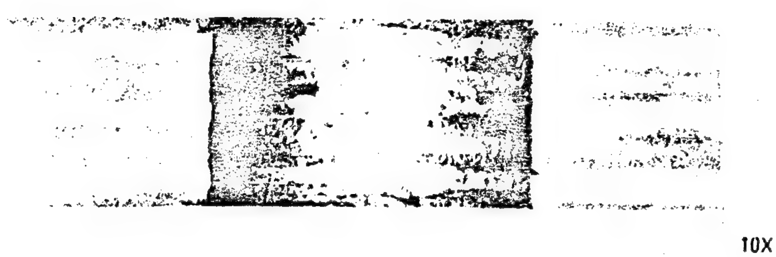

Figure 28. - Macrophotograph of failed chipout fatigue specimen I-51R sectioned after testing

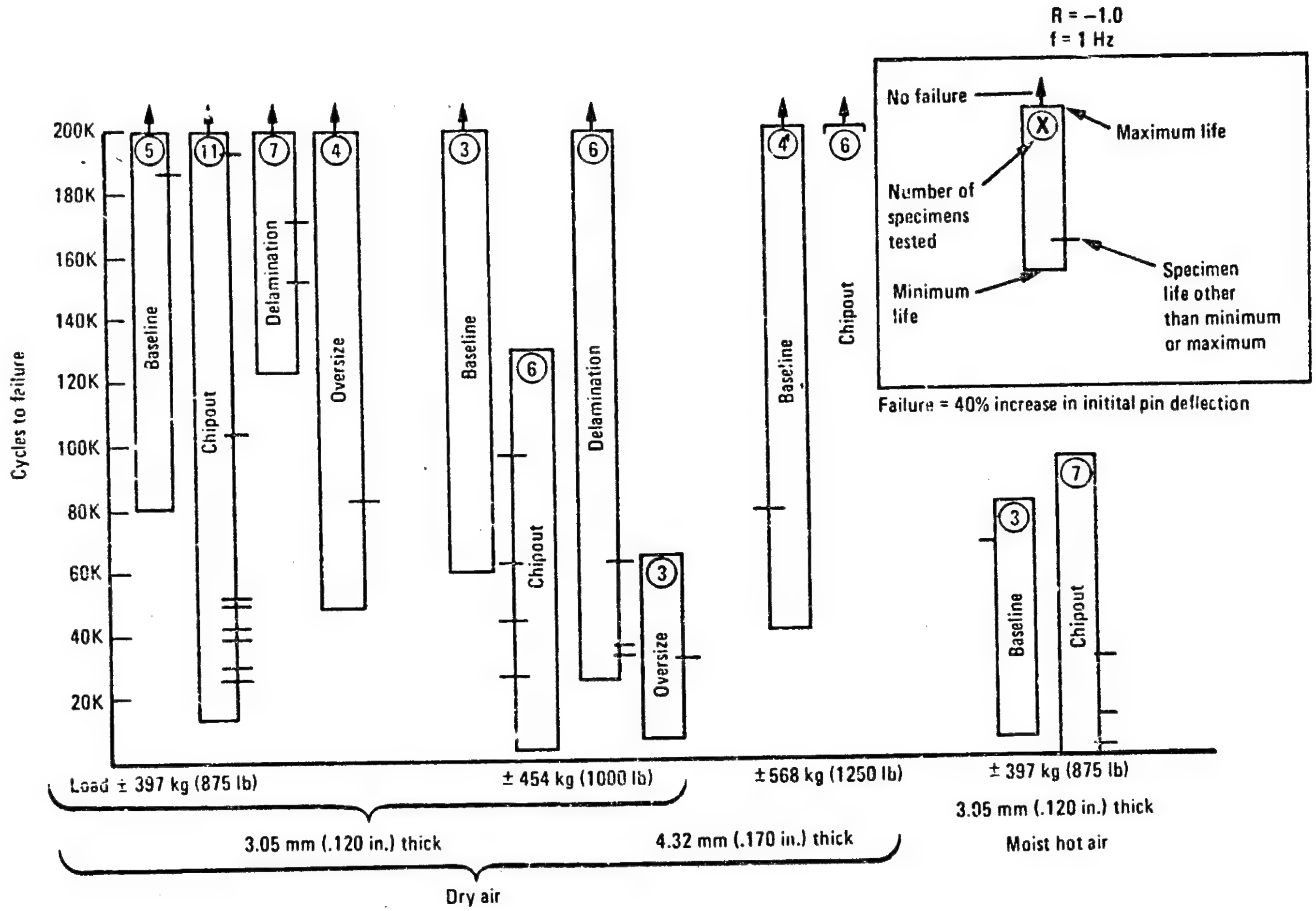

Figure 29. - Summary of pin loaded reverse cycle fatigue test results on T300/5208 graphite/epoxy - 4.84 mm (3/16.) hole

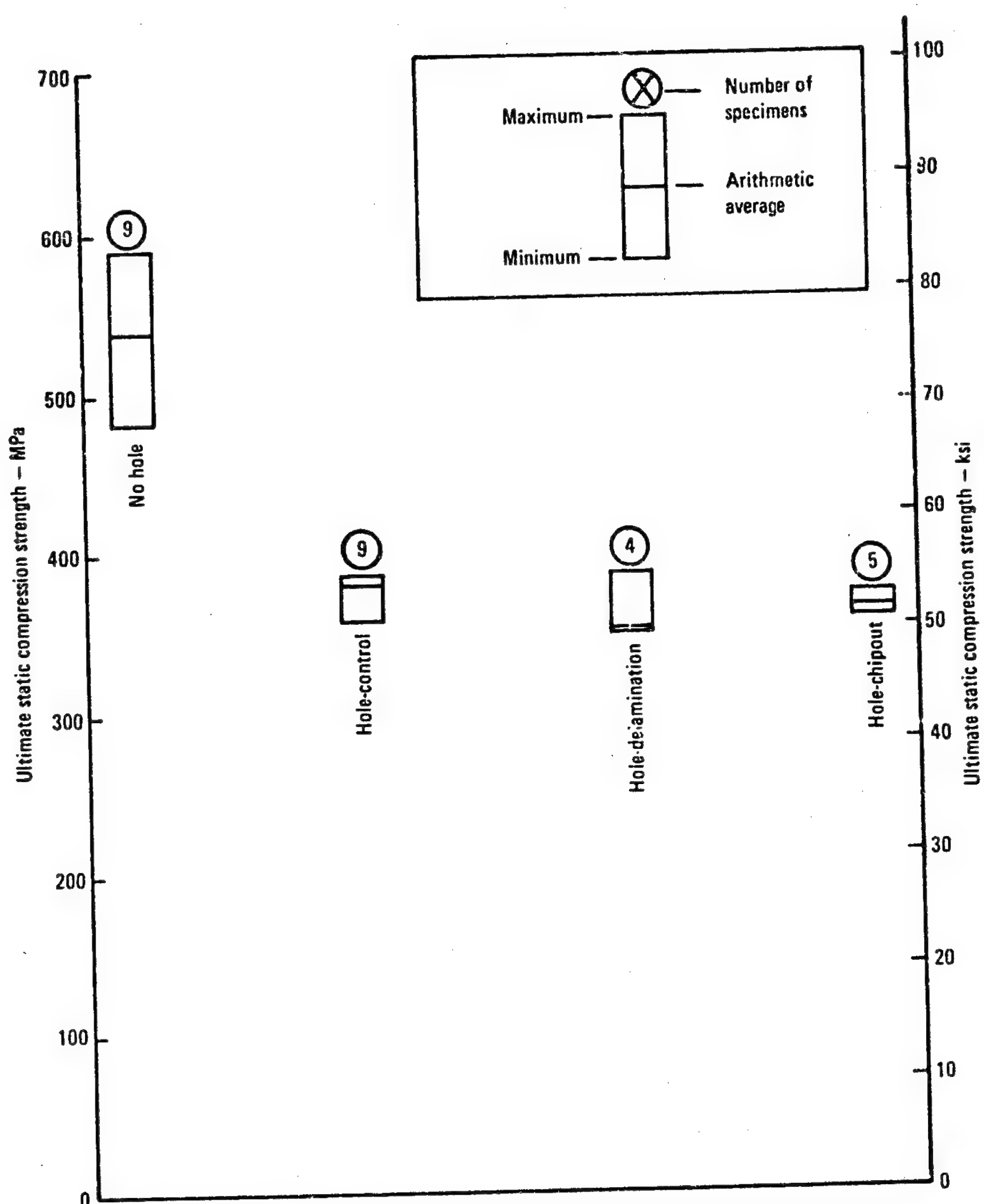

Figure 30. - Summary of ultimate static compression tests.

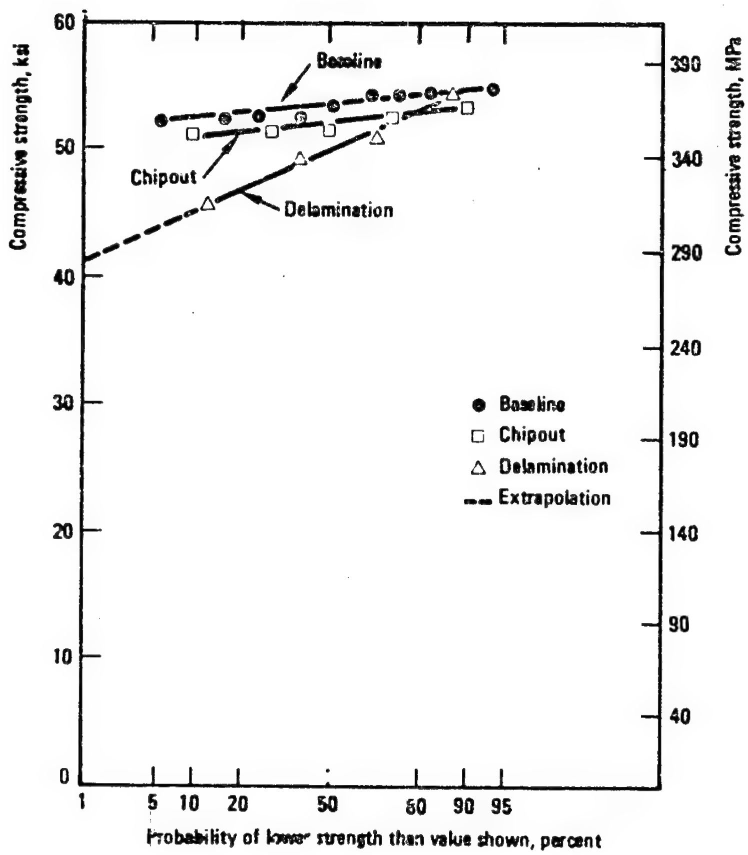

Figure 31. - Compression strength plotted on probability paper.

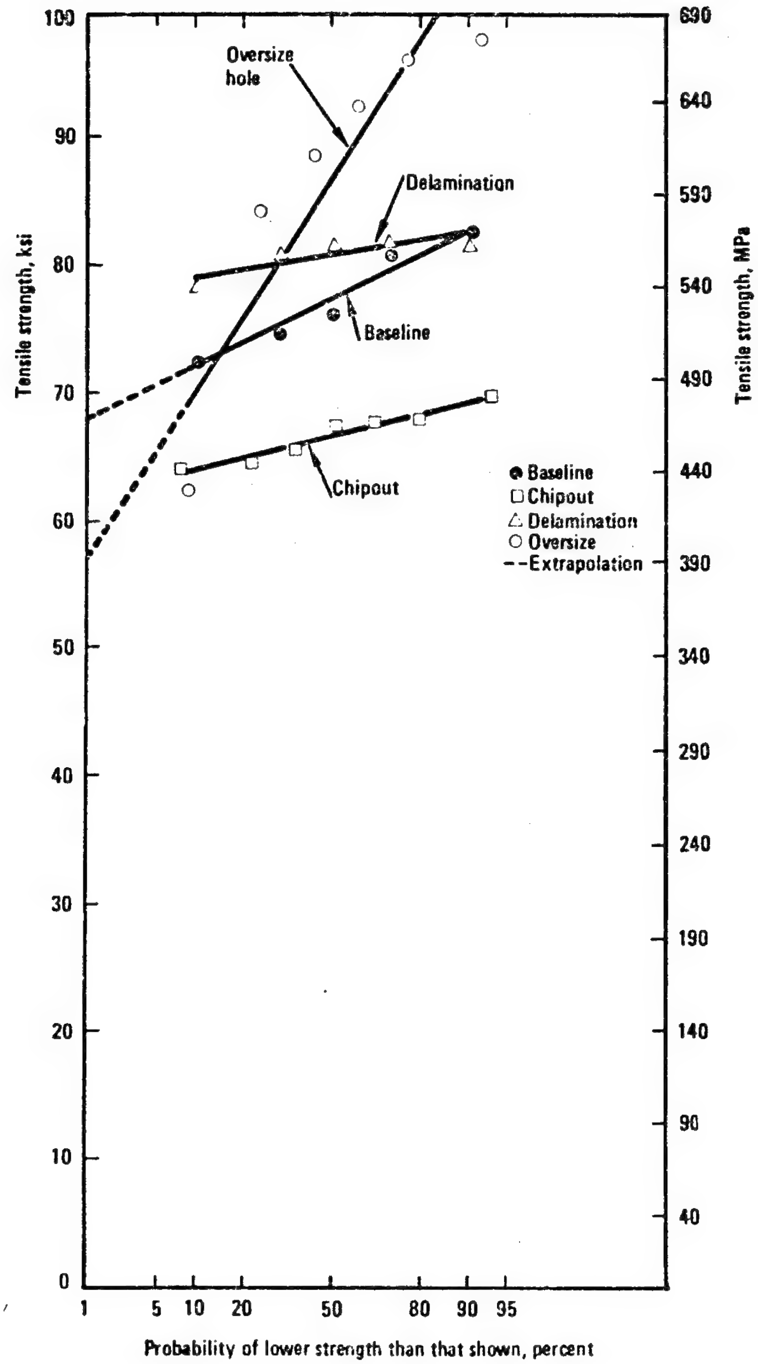

Figure 32. - Dry air tensile strength of 3.05 mm (0.120 in.) thick specimens plotted on probability paper.

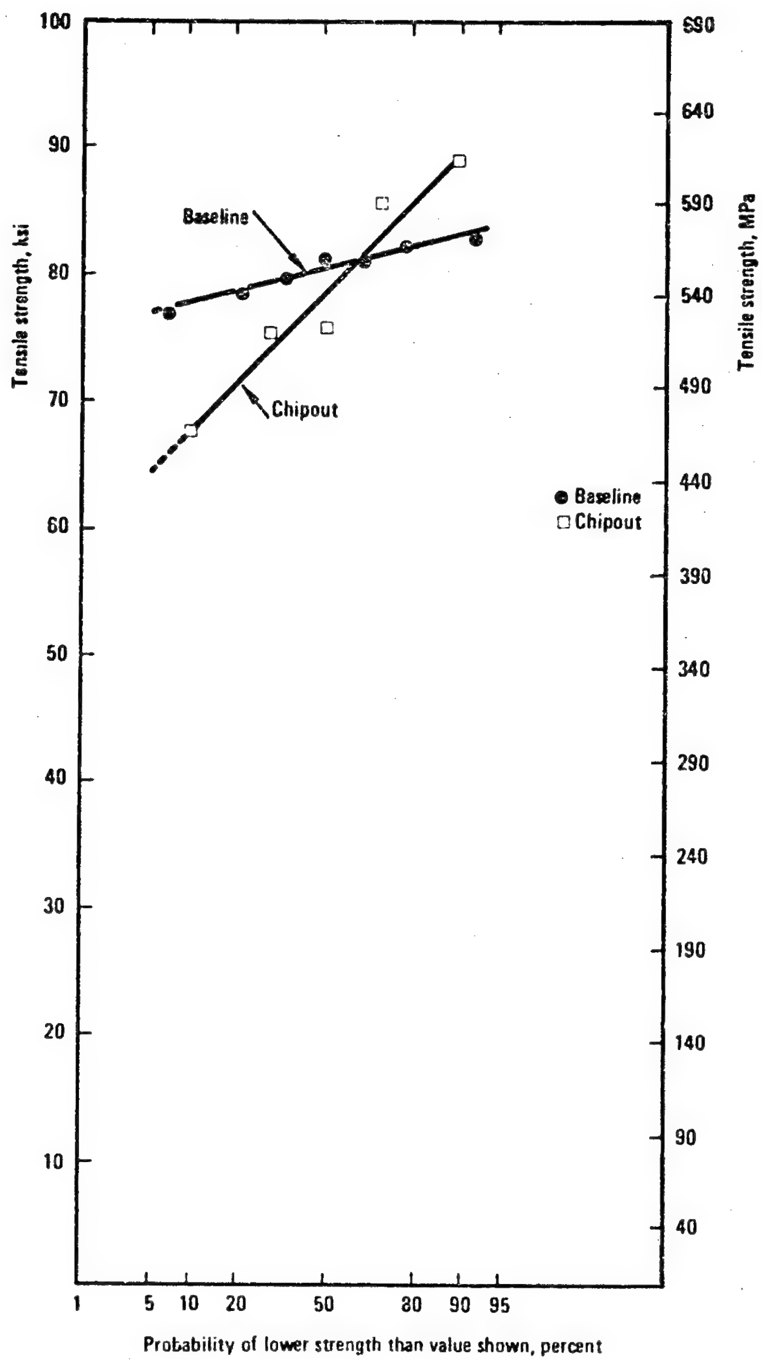

Figure 33. - Dry air tensile strength of 4.32 mm (0.170 in.) thick specimens plotted on probability paper.

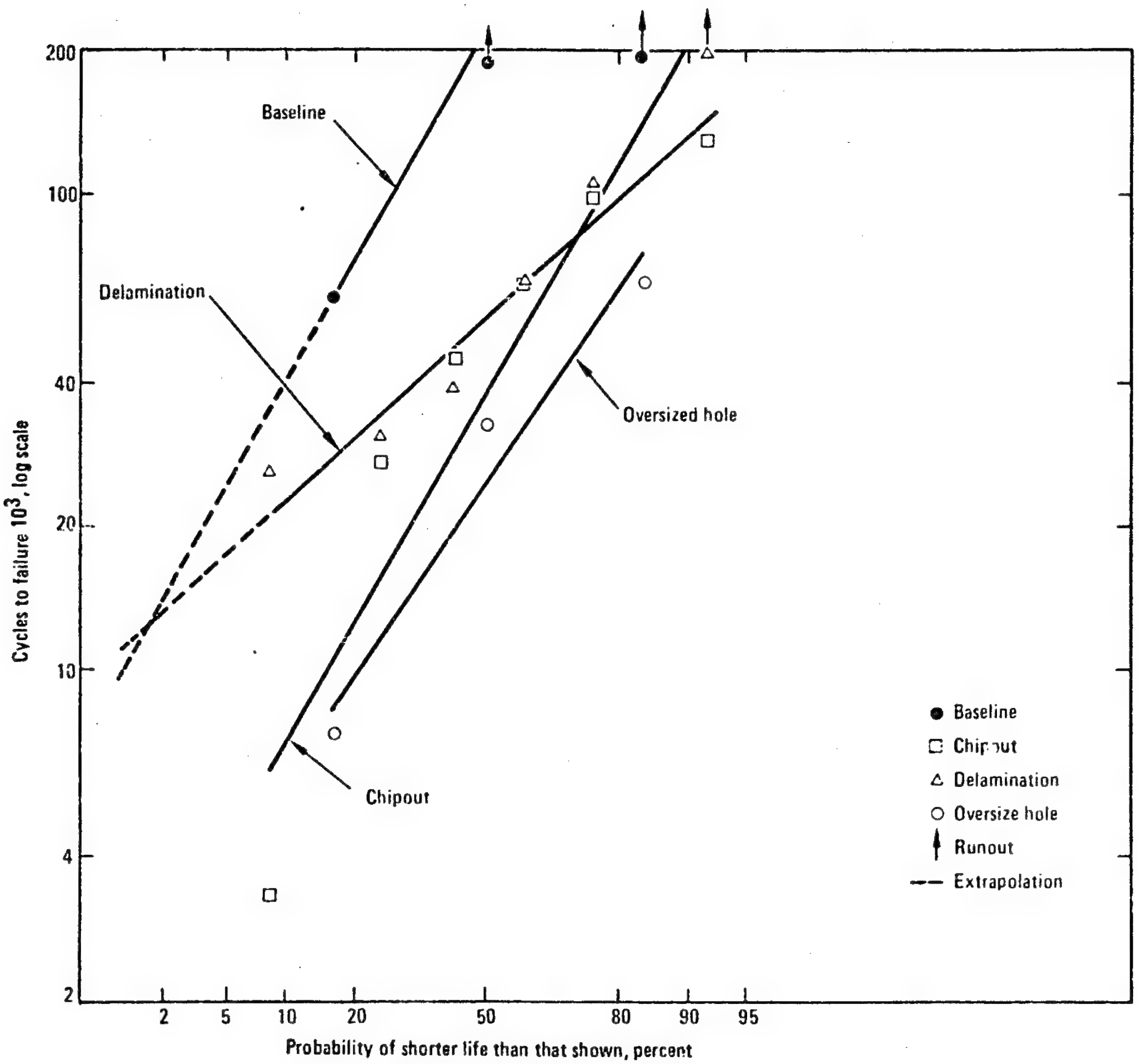

Figure 34. - Dry air fatigue life of 3.05 mm (0.120 in.) thick specimens tested at ± 454 kg (±1000 lb) plotted on probability paper.

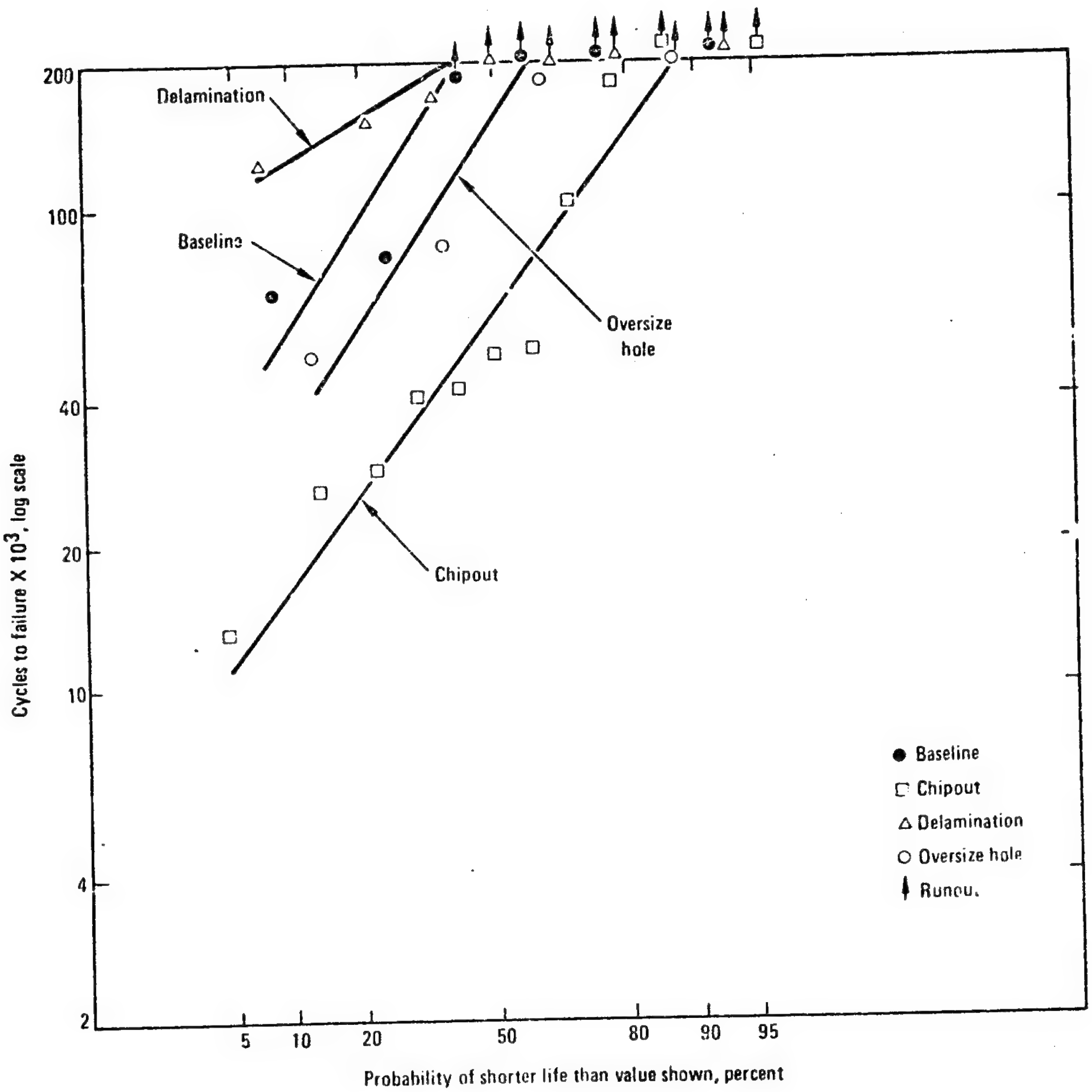

Figure 35. - Dry air fatigue life of 3.05 mm (0.120 in.) thick specimens tested at ± 397 kg (± 875 lb) plotted on probability paper.

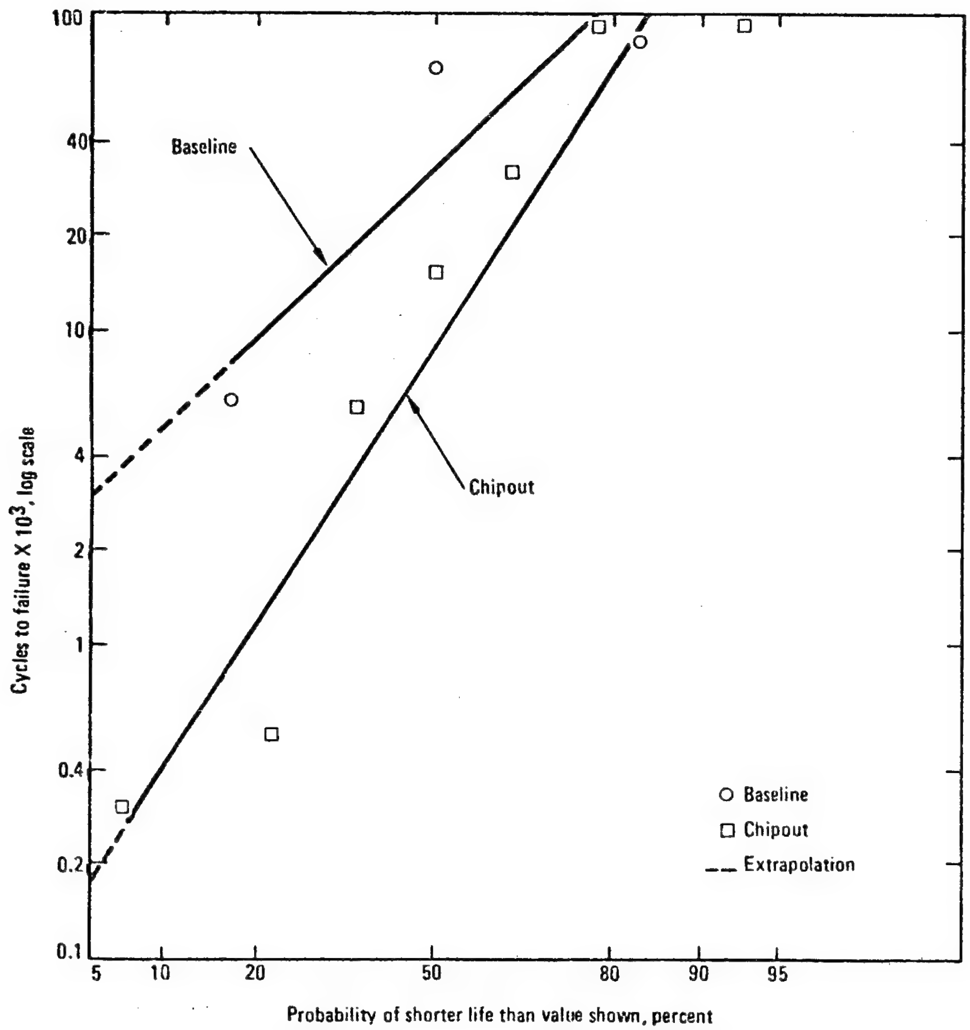

Figure 36. - Hot moist air environmental fatigue life of 3.05 mm (0.120 in.) thick specimens tested at ± 397 kg (±875 lb.) plotted on probability paper.

APPENDIX A

SUMMARY OF INDUSTRY RESPONSE TO QUESTIONNAIRE

An industry questionnaire was sent to the principal aerospace contractors currently involved in advanced composite technology. Seventeen responses have been received or a 58% return rate.

The questionnaire was divided into four categories. The analysis of the response is as follows:

PREMISE AND BASIC DATA

1. Questionnaire is directed at determining your experiences in the making of holes (various sizes) countersinks and counterbores, in thin to thick cured graphite/epoxy (various resins and fibers) composites.

2. Hole Fabrication Experience and Parameters. Fill in as applicable:

	Hole Size Range		Composite Thickness Range		Graphite/ Epoxy System
Research	min	max	min	max	
Development Prior to Production					
Production					

Response:

Hole size ranged from 0.04 to 1.500 inches in diameter. Thickness ranged from 0.005 inches to 1.250 inches. Eight responses reported using the T300/5208 Narmco graphite/epoxy system. The other responses reported using a wide variety of graphite/epoxy systems.

3. Do you have experience in "Hybrid Drilling" (metal and graphite drilled at the same time?) Yes______ No______

If yes, discuss, including metal alloys drilled and types of cutting tools used.

Response:

Sixteen reported experience in drilling metal and graphite. Metallic material includes aluminum, steel, titanium, and Invar. Straight flute and twist drills were used. Tool material was carbide and HSS. Two reported using carbide gun drills with cutting fluids.

HOLE FABRICATION PRACTICES

1. Drill or tool material used (including grade or designation.)

HSS

Carbide

Diamond

Other

Response:

All reported using carbide as a drill material. Ten reported using diamond tools and seven reported using various grades of HSS tool material. In the "other" category, material such as ceramic or borazon was reported.

2. Drill type or geometry (including parameters such as straight or helical flutes, point, margin, helix angle, etc.)

Response:

Majority reported using helix twist drills with helix angles varying from 10^{o} to 35^{o}. Point angle was either 118^{o} or 135^{o}. Others reported straight flute drills. Several reported proprietary drills. Curved or ogival point drills were also reported.

3. Drilling Units

Jig bore

Drill press

Spacematic, Quackenbush

Hand

Other

Response:

Fifteen reported using hand drills. Twelve use Spacematic and ten use Quackenbush production type units. Ten reported bench drill presses and two reported using jig bores for drilling.

4. Feeds and Speeds

Inches per revolution (IPR)	min	max
Surface feet per minute (SFPM)	min	max

Response:

Feed rates reported ranged from 0.0001 to 0.030 IPR and cutting speeds ranged from 5 to 1000 SFPM.

5. Coolants used if any Yes No

If yes, what type?

Response:

Majority reported using coolants for drilling. Coolants included Freon, soluable oil, and water. Five reported drilling dry and two reported using air.

6. Backup material on hole when drilling? Yes No

If yes, what material?

Response:

All reported using some form of backup material. Materials used included wood, aluminum, micarta, and phenolic.

7. Holes deburred? Yes No

If yes, how?

Response:

Eleven reported deburring holes using abrasive wheels, emery paper, countersinks or diamond tools. Balance reported not deburring holes.

8. Tool life constraints Yes No

If yes, describe, i.e., holes per sharpening, wearland, others.

Response:

Twelve reported limiting number of holes per drill sharpening or setting a wearland measurement. Balance do not set limits on drill usage.

9. Production tooling or fixtures used? Yes No

If yes, discuss briefly.

Response:

Eleven report using production tooling or fixtures such as drill plates or Spacematic templates.

10. Are Manufacturing Control type documents used?

Yes No

Are these available to the industry? Yes No

Response:

Thirteen report using manufacturing control documents, but only six of these are available to industry. Balance do not have control documents.

11. Are operators trained or certified? Yes No

Response:

Nine report operators trained and certified. Three report trained operators only and five report no training or certification of operators.

QUALITY CONSIDERATIONS

1. Hole dimensional tolerances?

   (May vary with size range or function, ie, Hi-Lok holes versus nut plate study clearance holes.)

   Response:

   Seven report a tolerance spread of 0.003 inch on holes. Others report tolerance spreads from 0.002 to 0.010 inch.

2. Inspection System?

   Please discuss including such parameters as visual, dimensional radiographic (x-ray) or ultrasonic C-scan methods.

   Response:

   Fifteen report using visual inspection methods and eleven use dimensional checks. Six use ultrasonic methods and three use radiographic.

3. Flaws or imperfections experienced (check as applicable)

   A Diameter
   B Angularity
   C Bellmouth
   D Barrelling
   E Out of Round
   F Roughness
   G Cracks
   H Chipout
   I Delamination
   J Overheating
   K Other

   Response:

   Out of ten possible flaws or imperfections, two reported nine flaws and ranging down to one report of one flaw.

4. Frequency of flaws in D3. Rate in ascending order of frequency, i.e., most 1, least 11.

   Response:

   Out of 17 questionnaires returned, the summary of #1, 2, and 3 flaw frequency is noted below:

4.

Flaw	Replies: Most Frequent	Second Most Frequent	Third Most Frequent
Diameter	3	3	2
Angularity	-	-	2
Bellmouth	-	-	2
Barrelling	-	1	-
Out of Round	1	1	1
Roughness	-	1	3
Cracks	-	-	2
Chipouts	8	1	1
Delamination	5	5	1
Overheating	-	2	-
Other	-	1 (mislocated)	-

5. What is primary cause for rejection of holes?

Response:

The most common reason for hole rejection was delamination followed by chipout.

6. Do you have an Accept/Rejection standard for holes?

Yes No

Can you describe it?

Response:

Fourteen reported having an Accept/Reject standard for holes. Nine of these went into some detail concerning the workings of the standard.

7. Is your Accept/Reject criteria based on substantiating test data?

Yes No

Are these data available to the industry?

Response:

Eleven reported basing the criteria on test data. A similar number did not respond to whether data were available to the industry. Four actually stated it was not available and one responded data would be shared with industry.

8. What type of measuring or inspection equipment is used to check holes?

Response:

Sixteen out of seventeen report using some type of gage. others use intra-mikes, borescopes or ultrasonic C-scans.

GENERAL

1. How do you classify the holes you have been producing (critical, regular, other?)

Response:

Eight reported classifying holes as critical, eight as regular and one as close tolerance or R and D.

2. What are considered as factors that produce a good hole?

Response:

Thirteen report the importance of the correct feed and speed plus a sharp correct geometry drill. To a less degree three reported importance of operator skills and coolants.

3. Would relaxation of Accept/Reject criteria reduce costs?

Yes No

If yes, discuss, i.e., types of tests that would permit relaxation.

Response:

Ten reported relaxation of Accept/Reject criteria would reduce costs. Only a few offered any discussion on types of tests that would be required.

The following is a list of the companies and the responsible individual who returned a questionnaire:

AVCO Aerostructures Division
P.O. Box 221
Nashville TN 37202
A.V. Forte (615) 361-2413

Boeing Commercial Airplane Company
P.O. Box 3707, Mail Stop 3810
Seattle WA 98124
Joseph L. Phillips (206) 433-1565

Boeing Vertol Company
P.O. Box 16858, Mail Stop P62-06
Philadelphia PA 19142
Robert L. Pinckney (215) 522-3690

Douglas Aircraft Company
3855 Lakewood Blvd
Long Beach CA 90846
N.R. Williams (213) 593-7301

General Dynamics/Convair Aerospace Division
5001 Kearny Villa Road
San Diego CA 92138
Charley Maikish (714) 277-8900 Ext. 1877

General Dynamics/Ft. Worth Division
P.O. Box 748
Fort Worth TX 76101
L.J. Hawkins (817) 732-4811 Ext. 4461

Grumman Aerospace Corporation
Bethpage LI NY 11714
Sidney Trink (516) 575-7362

Lockheed Georgia Company
86 South Cobb Drive
Marietta GA 30060
Mike Lindsey (404) 424-3721

Lockheed Missiles and Space Company
P.O. Box 504
Sunnyvale CA 94088
Carl Wilkins (408) 742-2310

Martin Marietta Corporation
Denver CO 80201
John R. Lager (303) 973-5271

McDonnell Douglas Astronautics Company
5301 Bolsa Avenue
Huntington Beach CA 92647
B.G. Leonard (714) 896-3801

Northrop Corporation
3901 W. Broadway
Hawthorne CA 90250
Robin Podder (213) 970-3497

Rockwell International
Los Angeles Division
International Airport
Los Angeles CA 90009
Chuck Dowling (213) 670-9151 Ext. 3674

Rockwell International
Tulsa Division
P.O. Box 51308
Tulsa OK 74151
Charles J. Meinhardt (918) 835-3111 Ext. 2375

Sikorsky Aircraft Division of United Technologies Corporation
N. Main Street
Stratford CT 06602
Richard C. Prentice (203) 378-6361 Ext. 1567

Vought Corporation
P.O. Box 225907
Dallas TX 75265
J.M. Shelton Jr. (214) 266-4440

Lockheed-California Company
P.O. Box 551
Burbank CA 91520
Chuck Perkins (213) 847-4255

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5. M.S. Rosenfeld and S.L. Huang, "Fatigue Characteristics of Graphite/ Epoxy Laminates under Compression Loading, "AIAA J.Aircraft, Vol.15, No. 5, May 1978.

6. K.N. Lauraitis and P.E. Sandorff, "Effect of Environment on Compressive Strength of Laminated Epoxy Matrix Composites," AFML-TR-79-4179, December 1979.

7. L.J. Hart-Smith, "Bolted Joints in Graphite-Epoxy Composites," NASA CR-144899, January 1977.

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R. Tan:	Data plotting
S.G. Kracher:	Nondestructive inspection

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15. Supplementary Notes

Contract Monitor: W. Todd Hodges
NASA Langley Research Center

16. Abstract

A program was conducted to study the influence of hole quality on the structural behavior of composite materials. From an industry survey it was determined that the most frequent imperfections encountered during hole fabrication are chipout, delamination, and oversize conditions. These hole flaw types were generated in critical areas of static, compression, and fatigue specimens fabricated from T300/5208 graphite/epoxy system. The specimens were tested in static and cyclic pin bearing modes in addition to compression loading. Results of these tests are presented and discussed. The hole chipout defect reduced the static and cyclic endurance characteristics. Oversize holes also lowered the cyclic pin bearing endurance, but had no influence on the static pin bearing characteristics. Delamination had no insignificant influence on the static tension and cyclic pin bearing characteristics. Compression tests demonstrated a deleterious effect for chipout or delamination defects. Proposed hole quality requirements are discussed.

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